Dynamic Route Decision Model-based Multi-agent Evacuation Simulation - Case Study of Nagata Ward, Kobe

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ABSTRACT

In this research, involving local people's concerns in the decision on the evacuation route, a dynamic route decision model is proposed by explicitly considering group evacuation, landmarks & evacuation signs, and familiarity with the local environment. A spatial relationship-dependent approach is used to measure the difference in residents regarding local knowledge. To understand the people's decision-making process for evacuation routes, a survey was conducted with members of the Zonta Club in Japan. Based on the survey, a prototype version of a multi-agent simulation (MAS) system is developed for the case area, Nagata Ward, Kobe.

1. BACKGROUND

Regarding evacuation routes, the shortest-route method is widely used for evacuation simulation (Chen and Zhan, 2006; Takahashi *et al.*, 1989; Stern *et al.*, 1996; Katada *et al.*, 2004). The GIS network module is also a popular way to analyze the evacuation route (Tachi *et al.*, 2001). Moreover, some researches developed specific route choice models considering specific factors. For example, leadership was taken into account in the research of Ashibe (2006); Arai *et al.* (2003) then detailed the group-following behavior under a total chaos situation to evacuate from underground shopping centers. The difference in walking speed among age levels was taken into account and in this research, the following behaviors were separated into the autonomous type and the follow type. Ohata *et al.* (2007) used the minimum angle as the moving direction. In their research, agents were classified into two types. One type is supposed to know where the shelter is, and the other is not. Communication between the two types is set as to whether the second type knows someone who belongs to the first type. Through the simulation, they evaluate the configuration of the shelters against tsunami disaster in Kushiro City. Besides these, many research works has been conducted considering traffic capacity during evacuation (Lu *et al.*, 2003; Thomas and Justin, 2003).

Unfortunately, few researchers consider the difference in environmental cognition of residents' evacuation behaviors in their simulations. As we know, an individual evacuation plan varies in the decision on evacuation route, starting time of evacuation, intended shelter, etc. In order to understand people's concerns regarding evacuation shelters and routes, a survey was distributed to the Nagata Elementary School community in Nagata Ward, Kobe, where residents suffered the Great Hanshin-Awaji Earthquake in 1995 (Takeuchi *et al.*, 2006). The result shows that almost all people know where the shelter is and more than 84 percent of people deem the distance to a shelter as a very important factor among 45 valid answers. From the survey result, we also found that even residents who live in the neighborhood may take a different route to a shelter. This proves that individuals hold their own local knowledge that is formed by their daily life. It is necessary to involve local people's concerns in the decision on evacuation route in the simulation.

In this research, a dynamic route decision model is proposed to highlight the decision process with multi-factors including familiarity, group evacuation, and landmark & evacuation signs. A spatial relationship-dependent evaluation method is used to quantify residents' familiarity with the local road network. For accompanying behavior, evacuees adopt both the autonomous type and the follow type. Based on this model, a multi-agent simulation (MAS) system is developed using KKMAS [KKMAS homepage], a MAS platform for Nagata Ward, Kobe.

2. DYNAMIC ROUTE CHOICE MODEL

In this research, the hazard is a flood inside a levee due to a flash storm. Barriers caused by inundation, flooded roads, and collapse of buildings may block off an evacuation route. We assume that a barrier may happen anywhere among the road network and that the blocked status may remain during the simulation. If a person is surrounded by barriers, it will be viewed as a failure of evacuation. So, the problem becomes how people make their own decisions in route searching.

The road network consists of blocks (*cho*) that can be subdivided into sub-blocks (*chome*) as shown in the black circle in **Fig. 1**. According to population data in each sub-block and the evacuation ratio, evacuees are evenly distributed within the nodes in each sub-block (*chome*). For common nodes between each sub-block, the number of people gathering at two nearby sub-blocks will be equal. People are assumed to evacuate from each node (blue) that

KEY WORDS: dynamic route decision model, multi-agent, evacuation simulation, survey

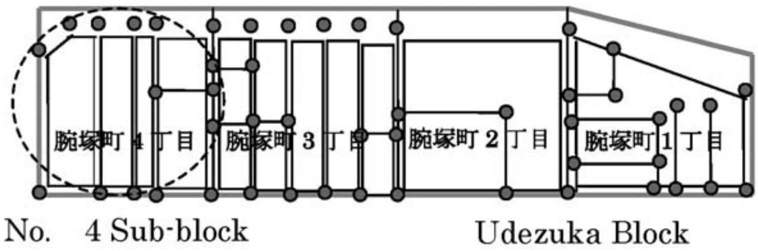

Fig. 1 Block and sub-block

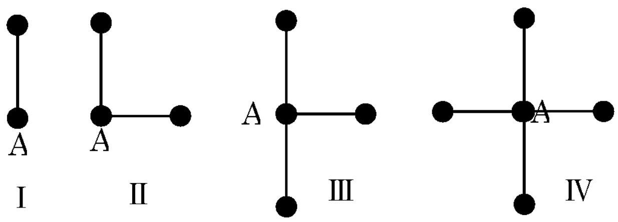

Fig. 2 Junction type

represents a crossing, starting point, or terminal of a road in the road network. People will move on the links connecting two nodes.

Basically, there are four junction types as shown in **Fig. 2**. For I, there is only one choice for people who stay at Node A. But for II, III, and IV, possible choices increase from two to four. In the current research, we treat the topographic condition as homogeneous.

"Dynamic" can be understood in two ways. On the one hand, a decision is made step by step when people move from one node to the next reachable and appropriate node; on the other hand, interactions among evacuees are dynamic processes. The model consists of the following sequential piecemeal decision-making problems for each node j where an agent is assumed to make a choice of links to the next node.

$$\max_{l_j \in B_j} \left\{ U_{l_j} = \sum_{i=1}^{n} W_i V_{il_j} \right\}$$

Here, U_{l_j} is the degree of efficiency for road choice making; i is each factor that affects people's decision on the evacuation route; l_j is links connected with node j that is barrier free; n is the number of total factors considered (in this research, n is equal to three); W_i is the weight of factor i; V_{il_j} is the evaluation values of reachable link l_j regarding factor i; B_j is the set of links blocked by the hazard; and $\overline{B_j}$ is a complement of set B_j, so $\overline{B_j}$ is a set composed of all reachable links connected with node j.

In the case study, three factors including familiarity, group evacuation, and landmarks & evacuation signs are considered. Landmarks & evacuation signs are usually marked in the form of an arrow that suggests the direction toward a formal shelter. The characteristics of group evacuation are described. Familiarity then describes the preference of people for different routes.

2.1 Priority among the factors

Robert and John (2003) proposed a conceptual framework for modeling variability in human behavior. Based on this framework, in the case study, evacuees are classified into two groups: one is residents and the other is non-residents such as travelers, commuters, or foreigners who are not familiar with the local environment. Different from residents, these non-residents may even not know where a shelter is and how to get to a shelter when a disaster happens. The level of local knowledge leads to different priority order in evaluating routes. Regarding the priority order of factors, a survey was conducted with 20 members of the Zonta Club in Kyoto. The following lists information on the survey.

- Date: Oct. 11, 2006
- Object: Members of the Zonta Club, a total of 20 persons
  All members are females of 30 to 70 years old living in Kyoto. Among them, 35% suffered slightly due to the Hanshin- Awaji Earthquake in 1995 and 5% suffered flood disaster in 2004 by Typhoon No. 23.
- Survey content: Previous disaster experience, evacuation activity, and shelter planning-related considerations
- Survey format: First giving a presentation to understand the context and then conducting the survey

The factors are listed as follows: familiar road as usual, the direction neighbors are heading in, landmark to a shelter, road width, moving distance, inundation situation, hazards along the road such as landslide and others. In order to identify the two types of agents' concerns on the decision on an evacuation route, the following two questions are used in the questionnaire. One is, "If a flood disaster happens, you decide to evacuate. Please select factors that you think are important for you in choosing the evacuation route and write the priority order," and the other question is, "When a flood disaster happens, how do you choose an evacuation route if you are in a place that you are not familiar with? Please select your choice and write the priority order."

For significantly high-weight factors see (a) Residents, and (b) Non-Residents in **Fig. 3**. This shows that for residents, significant factors ranked in order of priority are familiar landmark & evacua-

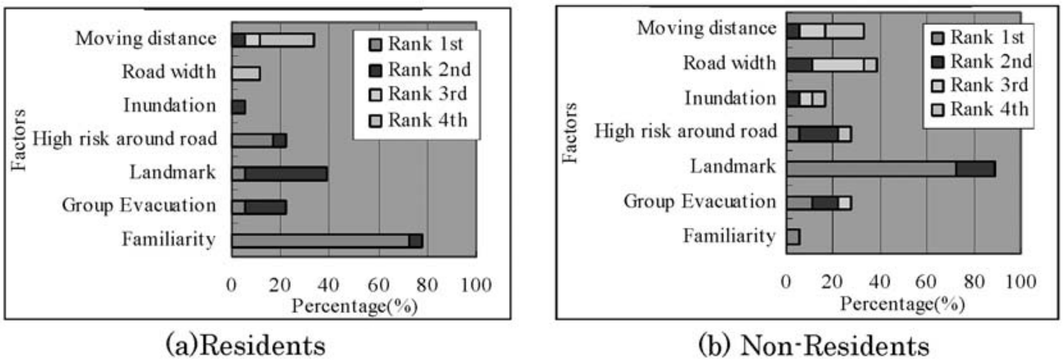

Fig. 3 Result of survey regarding the ranking of factors

Table 1 Weight of factors

Agent type	*Familiarity*	*Group evacuation*	*Landmark & evacuation signs*	High risk around road
Residents	0.58	0.11	0.17	0.14
Non-residents	0.05	0.15	0.68	0.12

tion signs, high risk around the road, and accompanying persons. On the other hand, for non-residents, the ranking becomes landmark & evacuation signs, accompanying persons, high risk around the road, and road width, in order of priority.

Based on the results shown in **Fig. 3**, the following equation is used to calculate the relative weight of factors.

$$W_i = r_{1i} + 0.5r_{2i} + 0.25r_{3i} + 0.125r_{4i}$$

Here, W_i represents the integrated weight value, and

r_{ji}, j = 1, 2, 3, 4 represents the percentage of each rank regarding factor i respectively. Thus, we obtain the weights of each factor for different agents as shown in **Table 1**.

2.2 Evaluation of each factor

Each factor was evaluated as follows;

- Landmark & evacuation signs
  V_{0l_j}= 1 if landmark & evacuation signs exist at link l_j; otherwise, V_{0l_j}= 0
- Group evacuation
  V_{1l_j}= 1 if more than three agents gather at link l_j; other wise V_{1l_j}= *Group Member Num*/3.0. Different from the research by Arai K. *et al.* (2003), we set a threshold for people to decide to follow others.
- Familiarity

In this research, people are assumed to follow the direction that conforms to the spatial relationship between the current position and the intended shelter. **Fig. 4** shows the process of calculation of factor-familiarity with the local environment.

Taking a GIS space as an example, an evacuee now stays at Node No. 260 and he intends to go to a shelter called Shinyo Elementary School denoted by Node No. 237.

There are four choices: No. 32, No. 93, No. 119, and No. 118 as shown in **Fig. 5**. In terms of spatial relationship, "outside" means that neither the X nor Y coordinate is inside the scope of the rectangle that is surrounded by the current node and destination node, so the evaluation value is set to -1 so that No. 32. "inside" means that both the X and Y coordinates are within the scope of the rectangle and the evaluation value is set as 1. "Partial" means that either the X or Y coordinate is within the scope of the rectangle. In this case, the evaluation values depend on the angle among the judged node to the current node to the destination node as shown in the above sketch map. V_{2l_j}, the evaluation value of familiarity, is defined as the cosine of the angle.

The smaller the angle is the closer to a straight line between the current node and the destination node the moving direction is. Correspondingly, the evaluation value becomes bigger. The method effectively keeps the distance to a destination within a controllable scope of changes. When more than one link has the maximum evaluation value, the probability function will be used to choose one among all backups. From a statistical point of view, the selection process can be viewed as a random decision making process for an agent.

2.3 Definition of agents

In the case study, from a behavioral point of view, agents are classified into residents and non-residents. This study area is read circle area in **Fig. 6**. This area is sevens local community (Chome). **Table 2** shows each Chome's household and population. Every Chome's formal shelter is "Shinyo Elementary School". As described above, residents are supposed to be familiar with the local environment and non-residents are those who are new to the environment. So, the difference in local knowledge leads to different evacuation behaviors between them. From an evacuation capacity point of view, agents are classified into "old," "young," and "child" types as shown in **Table 3**. As a parameter, the ratio of residents to non-residents is used to calculate the number of non-

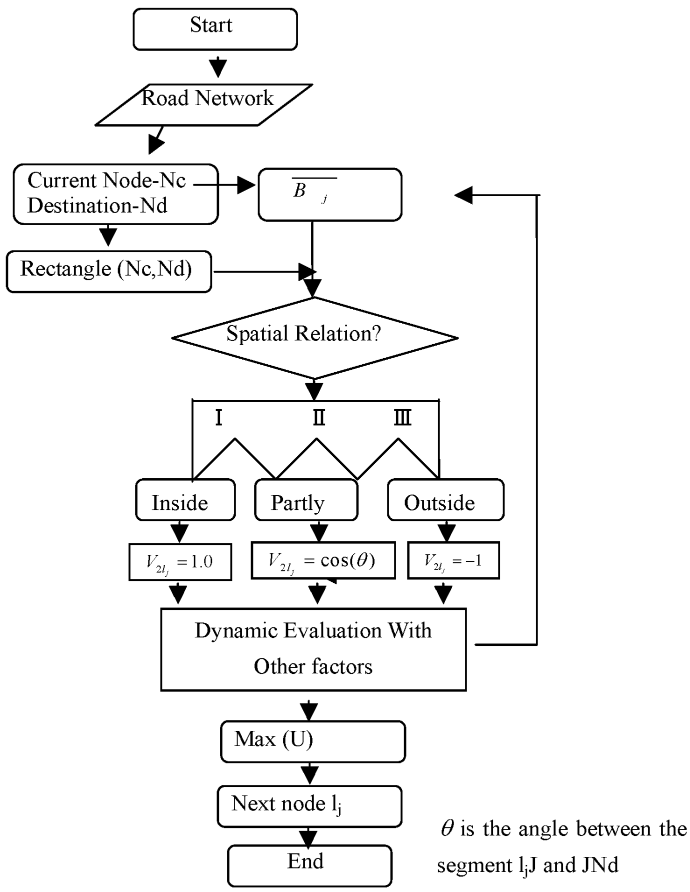

Fig. 4 Caluculation flow chart of dynamic route decision modeling

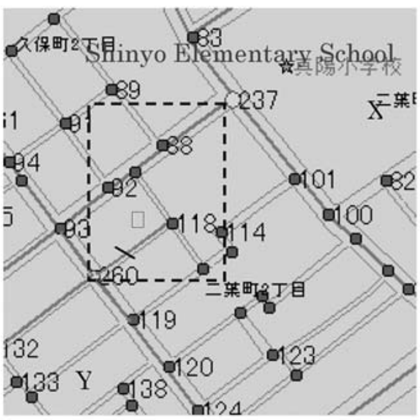

Fig. 5 Sketch map of calculation

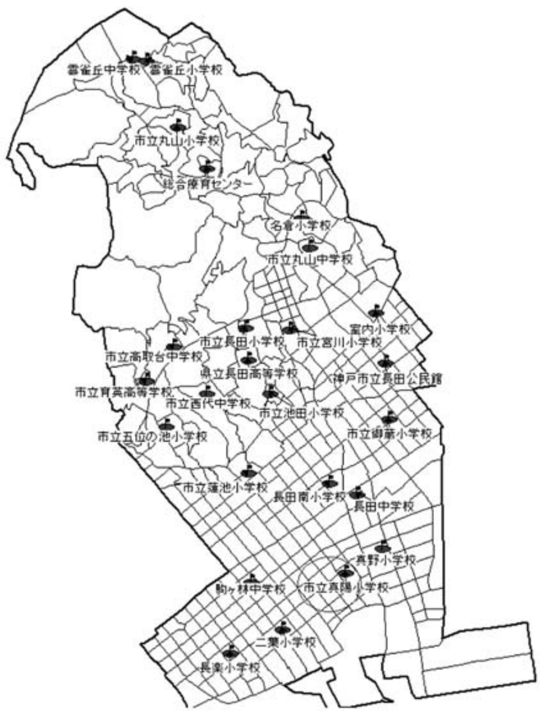

Fig. 6 Map of the case area in Nagata Ward, Kobe

residents and the detailed type of non-residents is randomly set in the simulation.

A household is viewed as the simulation unit and the simulation step is defined as one second. In the simulation, we suppose that all agents will evacuate to a shelter on foot, and walking speed depends on the type of household. For the "old" type, the walking speed is set as 0.8 m/s, for the "young" type, it is set as 1.4 m/s, and for the "child" type, it is set as 1.0 m/s. When the evacuation ratio changes, the total number of evacuees for each household type will automatically be calculated and put in the two-dimensional simulation space.

2.4 Simulation model

In this case area, there is only one formal shelter called Shinyo Elementary School. **Fig. 7** shows active rule of residents (a) and

Table 2 Spatial region scope of the case area

Cho name	*Chome*	*Formal shelter*	*Household*	Population
Udezukacho	1-4	Shinyo Elementary School	465	899
Kubocho	1-4	Shinyo Elementary School	482	919
Shiodacho	1-4	Shinyo Elementary School	557	1059
Futabacho	1-4	Shinyo Elementary School	587	1157
Komaecho	1-4	Shinyo Elementary School	78	139
Nishishiriikecho	3-5	Shinyo Elementary School	202	314
Total			2371	4487

Table 3 Agent type regarding population structur

Type	*Item*	*Percentage**	Type description
“Old”	Old couple	54.2	“Old” means that at least one family member is more than 65 years old.
	Single old person		
	Family with old people who are older than 65 years old		
“Young”	With a child of more than 6 years old	42.2	“Young” means that every family member is between 6 and 65 years old.
	Single		
	Couple		
“Child”	Family with a younger child of less than 6 years old	3.6	“Child” means that the family has children who are less than 6 years old.

* The percentage is calculated by statistical data on Nagata Ward from the Kobe website.

non-residents (b). When agents arrive at the node that represents the position of Shinyo Elementary School, the evacuation is viewed as complete. Interactive communication between residents and non-residents is considered in this research. If a non-resident decides to follow a resident, then a group is created as a moving unit. In this case, the two models are combined and the group will follow the decision of the resident, the leader in this group. When the group arrives at the target node, every member in this group is deemed to have finished evacuation.

2.5 imulation interface

In this research, based on KKMAS, a simulation system is developed. **Fig. 8** shows the main simulation interface. In this simulation, the variables include the block ratio, evacuation ratio, and ratio of residents to non-residents. In this case area, we assume the hazard to be a flood inside a levee by a flash storm and that the hazard remains at the same level with time by setting the spatial distribution of the flooded area before the simulation. The block ratio represents integrated environmental change by flood water, landslide hazard along the evacuation route, collapsed buildings, etc. Evacuees cannot pass through blocked roads and have to select another reachable road as the forward direction.

We assume that people will evacuate at the same time after receiving the first evacuation instructions. According to statistical population data, evacuees are evenly distributed in each *Chome*. Correspondingly, the number of each type of household is calculated. **Fig. 9** shows how the evacuation completion percentage changes with time.

2.6 Simulation results

As said above, there are three parameters in the current simulation system including evacuation ratio, block ratio, and ratio of residents to non-residents. In Case 1, the evacuation ratio is set at 30% and the ratio of residents to non-residents is set at 50:1. We compare the evacuation situation when the road is in a different block ratio respectively of 0%, 10%, and 50% (**Fig. 10(a)**). The simulation is run 10 times and the average results of evacuation completion are shown in the following charts.

The results show that the time consumed for evacuation completion increases with the block ratio changing from 0% to 10% to 50% (**Fig. 10(b)**). And they show a small change from the beginning but a rapid increase when the block ratio changes from 10% to 50%. And statistical successful evacuation also changes in a similar way. From 0% to 10%, there is no obvious change, but when the road network becomes worse, successful evacuation decreases rapidly.

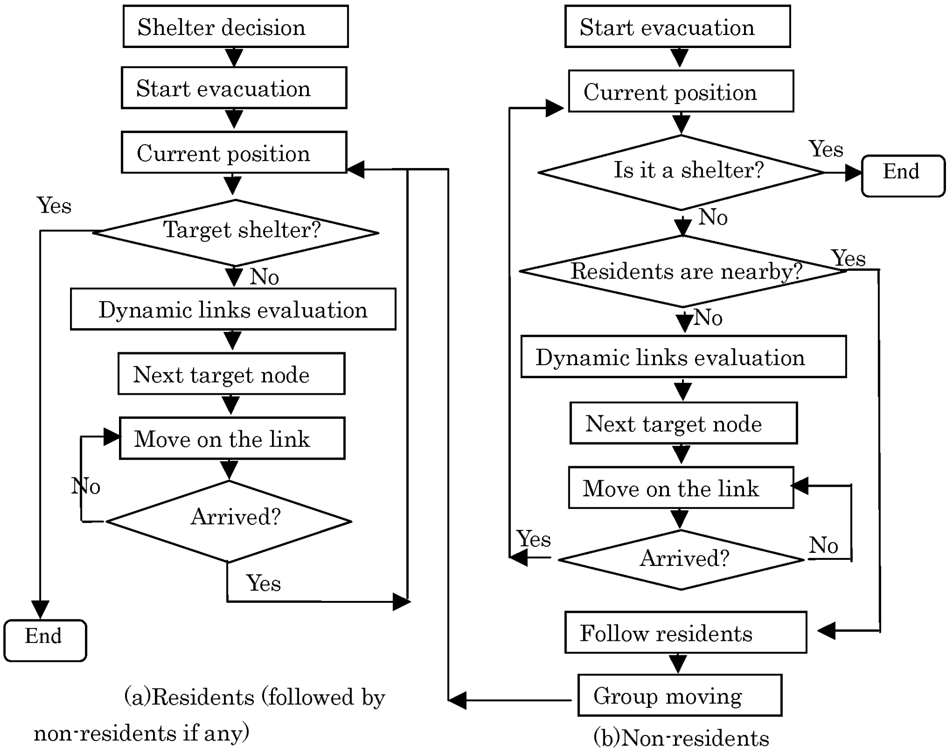

Fig. 7 Residents and Non-residents' activity rules

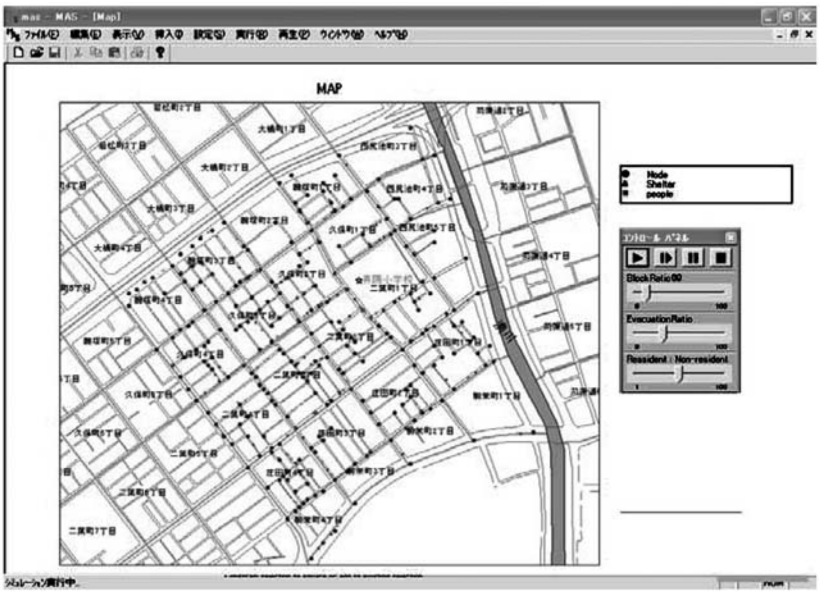

Fig. 8 Simulation interface

In Case 2, the evacuation ratio is respectively set at 10%, 20%, 30%, 40%, and 50% with the block ratio set at 10% and the ratio of residents to non-residents set at 50:1. **Fig. 11** shows the simulation results. When the evacuation ratio changes from 10% to 30%, the consumed time shows a slow increase but it becomes almost the same from 30% to 50% (**Fig. 11(a)**). Successful evacuations show a direct proportional increase with the evacuation ratio. From the above two cases, we also found that among all successful non-residents, 100% of them followed a group (**Fig. 11(b)**). It means that communication with residents plays a very important role in guiding non-residents to a successful evacuation.

The MAS system has been used as a medium in communication activities with people from the Zonta Club in Kyoto regarding evacuation issues. Most of the members showed great interest in the evacuation simulation, and the simulation process stimulated them to think about evacuation problems that they might face.

3. DISCUSSION AND CONCLUSION

In this research, involving local people's concerns in the deci-

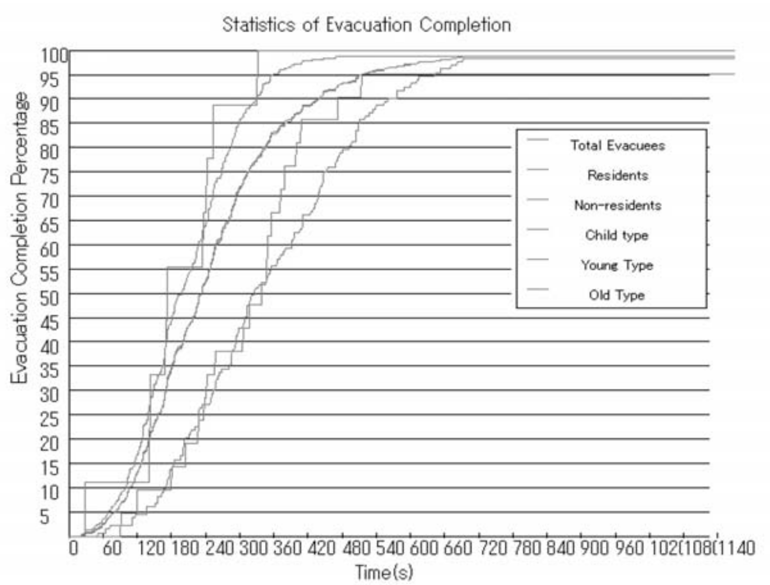

Fig. 9 Chart of the simulation process

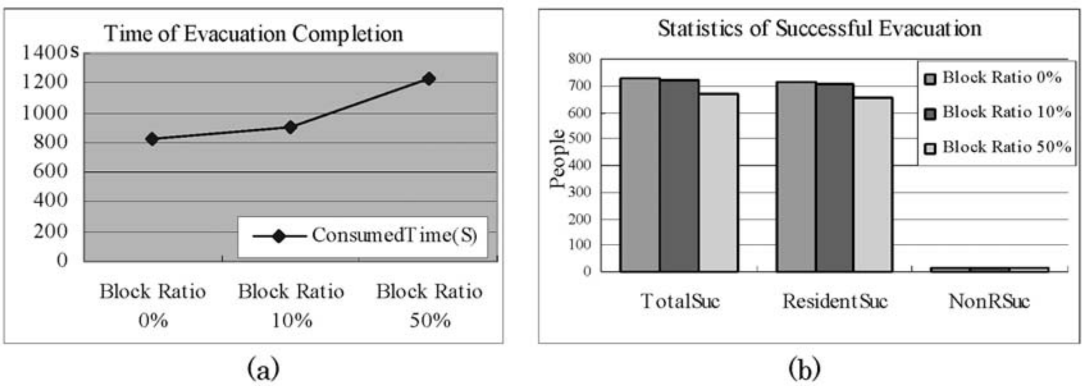

Fig. 10 Simulation results in Case 1

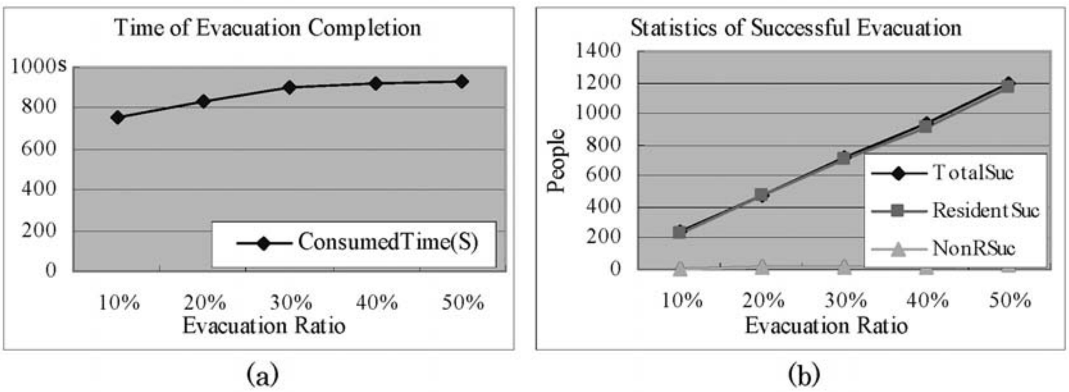

Fig. 11 Simulation results in Case 2

sion on the evacuation route, a dynamic route choice model is proposed considering group evacuation, landmarks & evacuation signs, and familiarity with the local environment. A spatial relationship-dependent approach is used to measure the difference in residents regarding local knowledge. Compared to some popular route-searching models such as the shortest-route method, the great advantage of the dynamic route choice model is that it explicitly involves people's ideas in the model and highlights individual differences in evacuation behaviors. A survey focusing on the route decision process was conducted to identify how people evaluate the importance of each factor, which provides us with a better understanding of people's evacuation behaviors. Based on the model, a prototype version of the multi-agent simulation system is developed with Nagata Ward, with Kobe as a case area.

In the current simulation, in place of analysis of the flooding process, the block ratio, a static parameter, is used to measure damage by flood disaster and all hazards are viewed as uniform and level. We intend to simulate people's evacuation behavior under a given hazard situation. But the lessons from pre-flood disasters showed us that many people died of sudden flooding water and soil collapse around the evacuation route during their evacuation. Additionally, one of the main reasons for non-evacuation is that people are greatly concerned about hazards along the evacuation route. So, as the next step, we will make efforts to integrate a flood model into the MAS simulation and detail the types and levels of existing hazards along each evacuation route.

Mutual help between residents and non-residents is considered in this research. Self-help and mutual help among residents, especially those vulnerable people for whom it is difficult to evacuate by themselves, however, are severe difficulties facing Nagata Ward. So, in order to empower the community, collaborative activities such as gaming, questionnaires, and workshops have been conducted with local residents. Based on feedback from respondents, simulation rules and models will be further improved and extended to incorporate more specifically residents' evacuation behaviors and concerns.

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