

Agent-Based Disaster Simulation Evaluation and its Probability Model Interpretation

Tomoichi Takahashi
Meijo University
ttaka@ccmfs.meijo-u.ac.jp

ABSTRACT

Agent-based simulations enable the simulation of social phenomenon by representing human behaviors using agents. Human actions such as evacuating to safe havens or extinguishing fires in disaster areas are important during earthquakes. The inclusion of human actions in calculating the damage at disaster sites provides useful data to local governments for planning purposes. In order to practically apply these simulation results, these results should be tested using actual data. Further, these results should be analyzed and explained in a manner that people who are not agent programmers can also understand easily.

First, the possibility of applying agent-based approaches to social tasks is shown by comparing the simulation results with those obtained from other methods. Next, we propose a method to present agent behaviors using a probability model and discuss the results of applying this method to the RoboCup Rescue simulation data. These will delve into future research topics for developing agent based social simulations to practical ones.

Keywords

Agent-based social simulation, evaluation method, probability model interpretation

INTRODUCTION

Agent-based approaches have enhanced the potential of computer simulations as tools for modeling and analyzing human behaviors from socio-scientific viewpoints. We are thinking that rescue work can be considered as a good application for agent-based social simulations (ABSS). Rescue work in the real world is important in saving human lives and comprises many agents. It involves search and rescue efforts, evacuations to safe areas, volunteer actions, and simulations of disasters such as fire spreading during earthquakes. The simulations involving human behavior and their interaction with disasters to decrease damages will yield useful tools and data for local governments to improve decision making.

A decade has passed since Jennings et al. overviewed the open issues and challenges in agent researches (Jennings et al.: 1998). Agents have been defined components of computer systems and ones that are capable of flexible autonomous action in order to meet their design objectives. The application of multi-agent systems (MAS) to practical applications entails demonstrating their validity to users. There are two ways of evaluating simulations: (1) using task-dependent standards or (2) using universal methods (e.g., statistics). The universal methods to evaluate the outputs of MAS and express the evaluation results in an easy-to-understand manner are one of the major issues in their application to social tasks. Considering the application to disaster and rescue simulations as an example, we will discuss the evaluations of ABSS.

This paper is organized as follows. In sections 2, the requirements of rescue management and rescue simulation are discussed. Section 3 illustrates the validation of ABSS by comparing local government reports and simulation results. A new analysis method based on a probability model and the applied results are discussed and presented in section 4.

REQUIREMENTS IN DISASTER RESCUE MANAGEMENT

From 2003 to 2007, six earthquakes and other disasters with more than 1,000 deaths have been reported. These disasters include (1) the tsunami caused by the earthquake in Northern Sumatra and (2) Hurricane Katrina that struck in 2005. In order to make towns safe from disasters, appropriate evacuation instructions need to be provided by the local governments, thereby saving human lives.

Disaster and rescue simulations

After the Kobe earthquake (1995), many Japanese local governments developed countermeasure plans for disasters; 44 of the 58 Japanese local governments estimated the damages that might be inflicted on their towns for anticipated earthquakes based on models studied in the civil engineering field (NLI: 1998). Disaster simulations mainly studied in the civil engineering field were used in these estimations. Damages to buildings or roads were simulated according to the seismic intensity of an earthquake. Further, these reports pointed out that volunteer actions were effective in reducing the damages and saving lives during the Kobe earthquake. The actions of humans, such as fire fighters and volunteers, are important in evaluating the damages and loss of human lives. A simulation involving human behaviors is required to estimate the disaster damages.

Requirements of the rescue system

When disasters occur, building collapses hurt civilians and block roads with debris. Fires burn houses, and smoke from these burning houses impede the activities of fire fighters. Figure 1 shows the image of a system that supports the local government to manage rescue operations. The lower box shows the physical world where the headquarters receive real-world data from sensors or civilians and commands their rescue teams to the sites. At disasters, communication networks may not function and the information might get snarled. It is desirable to know what is going on at the disaster sites at the time. The upper box is a system that supports decisions and management of the headquarters by simulating the damages and the human actions effect to the situations. The disaster and agent simulations are interacted with each other via a database that stores GIS data and properties of the situations. By checking the simulation results, the local government headquarters can make plans to deploy rescue agents and to evacuate civilians to safe places. Before the occurrence of actual disasters, the local governments also employ the simulation of disaster and rescue operations in order to improve the countermeasures against such disasters.

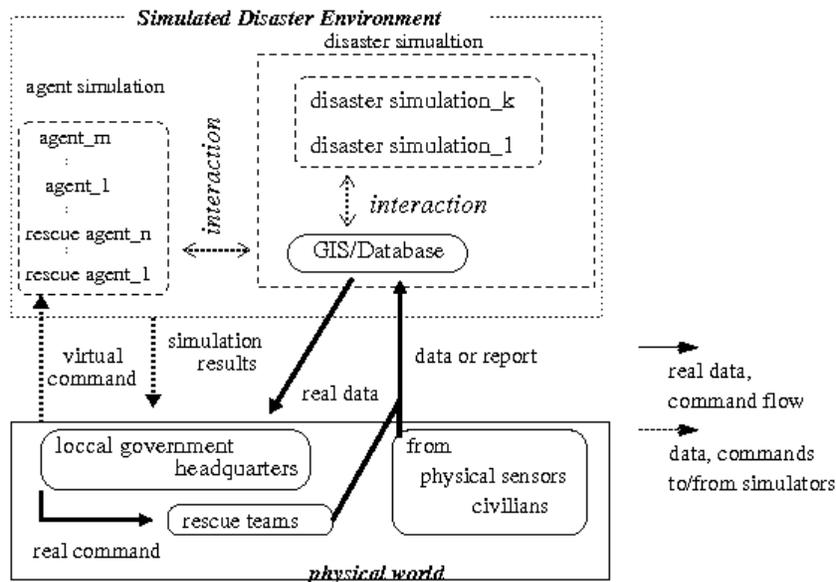


Figure 1. An Image of Disaster Rescue Management System

Validation required in social simulations

In scientific and engineering fields, the following principle has been repeatedly used to increase the fidelity of the simulations.

Guess → Compute consequence → Compare the experiment and simulation results

If the output of the simulations effectively matches the experimental data, the simulations are used as experimental tools. It is not possible to physically experiment with disasters on a real scale and involve humans as a factor. It is difficult to verify the results obtained from agent-based simulations that involve humans with the real data and to follow the obtained principle. It is important to demonstrate the validity of agent-based social simulation results and logically explain these results. By using the RoboCup disaster and rescue simulation as a case study, we discuss the

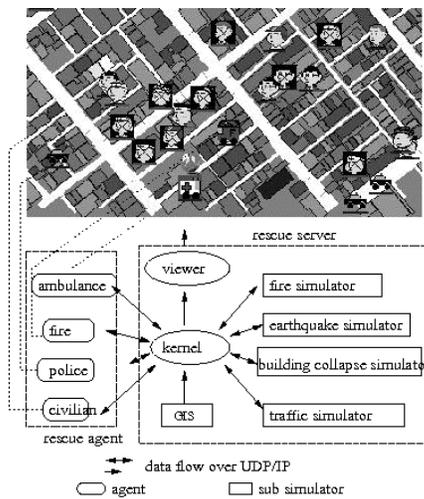
following points:

- (1) comparison of the agent-based simulation results with those obtained from conventional methods and
- (2) interpretation of the simulation results based on a probability model.

AGENT-BASED DISASTER AND RESCUE SIMULATION

RoboCup Rescue simulation as simulation platform and rescue operations implemented as agent behaviors

Kitano et al. proposed the RoboCup Rescue simulation (RCRS) that integrates various disaster simulation results and agent actions (Kitano: 1999). We use RCRS as a simulation platform that simulates the behavior of civilians and rescue teams in disaster situations (Figure 2). We implemented two types of agents: civilian and fire fighters. Civilians evacuate to safe places and are sometimes involved in rescue work. Fire fighters reach places from where they receive urgent calls or to search victims. They are coded to operate at least at messy disaster sites without specific knowledge about these areas. Improvements in these agents and collaborations among them are interesting topics; however, they are not investigated in this paper. The following basic behaviors have been implemented.



```

firefighter(){
    sense or receive commands from other fighters;
    report injured people to others;
    if(water tank is empty) supply water;
    if(near fires) extinguish;
    if(knows the fire locations) move;
    search (fires);
    search (victims);
}

```

Figure 2. RCRS architecture and base codes of fire agents

We select Nagoya city (the location of our university) as the test area. The Nagoya Fire Department published a report on damages from anticipated earthquakes with magnitudes 7–8. They estimated the number of fires that would occur and the number of houses that would burn. Figure 3 shows the snapshots of the RCRS simulations. The figures on the left show two neighboring wards—Nishi and Nakamura—of the 16 wards in Nagoya. Red marks denote the fire agents. The agents search the regions affected by fires and extinguish them. It was revealed that the introduction of fire-fighter agents generates a significant difference in the simulations, and the obtained results become comparable to the values presented in the report (Takahashi: 2006).

Comparison between ABSS and other methods and the discussions

Most local governments, not only Nagoya, estimate the damages to their administrative areas. However, disasters are spread over the boundaries of their administrative area. The middle image shown in Figure 3 is a composite map of the Nishi and Nakamura wards. The image on the right is the middle-bottom section of the image in the middle. Houses are built densely in this area. The local government designates this area as one of the most disaster-prone areas and wants to simulate the rescue scenarios for this area.

Table 1 shows the simulation results. The two columns of the GIS network provide the number of nodes and edges of the GIS maps of the ward. They are on a scale of 1:25,000. The local government estimated the damages for two cases: (1) earthquakes occurring during the nighttime and (2) those occurring during daytime. The third column provides the numbers of fires occurring at nighttime and daytime. The locations of fires are distributed, as suggested in the report. The fourth column provides the estimated rate of the burned areas from the local government report. The last columns provide the rate of burned areas obtained from the simulations. The values under “No Ffighter”

represent the simulation results with no fire-fighter agents, while the values under “Firefighter” are the results obtained when 40 fire-fighter agents were involved. By using the same random seeds in the simulations, the mechanism of a distributed simulation of the RCRS induces some variations in the RCRS simulation results. The values in the table are the average values of 10 simulations, and the standard deviations are given in the parentheses.

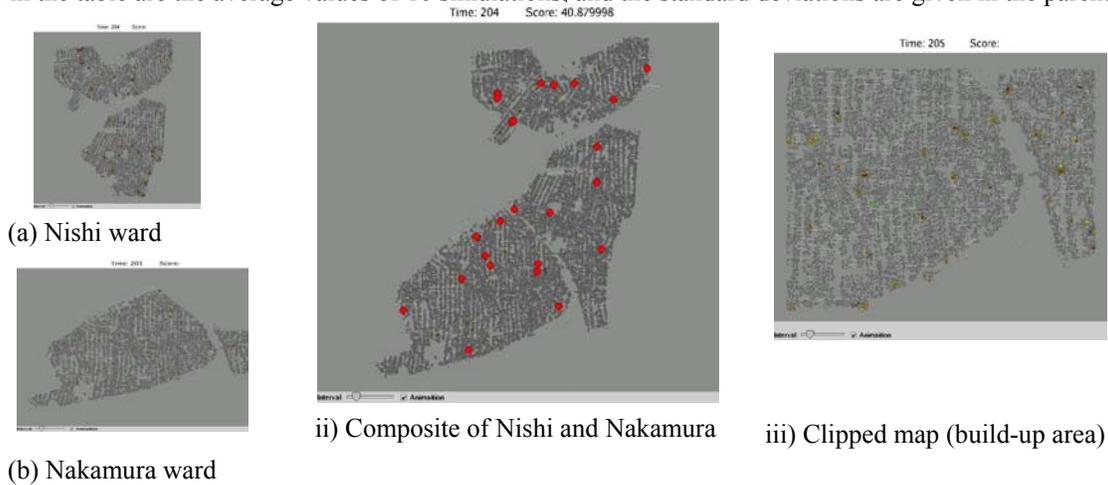


Figure 3. Snapshots of RCRS simulations (left and middle images show the administrative boundaries and the right image shows the clipped area)

| | GIS network | | No. ignitions | Estimation in the report | | Simulated burned area rate | |
|--|-------------|-------|---------------|--------------------------|-------------|----------------------------|--------------|
| | node | edge | | No Ffighter | Firefighter | No Ffighter | Firefighter |
| Nishi ward | 6,430 | 4,122 | 30 (night) | 4.19% | 3.34% | 8.53% (.00) | 8.08% (.00) |
| | | | 58 (day) | 8.56% | 7.31% | 13.4% (.07) | 12.96% (.03) |
| Nakamura ward | 6,044 | 3,766 | 22 (night) | 3.42% | 2.70% | 8.9% (.08) | 8.45% (.01) |
| | | | 45 (day) | 7.07% | 6.30% | 15.64% (.11) | 15.23% (.02) |
| Correlation with local government's estimated data | | | | | | 0.89 | 0.92 |
| Clipped area | | | 23(night) | | | 3.9% (.40) | 3.8% (.45) |
| | | | 45(day) | | | 7.2% (.00) | 7.14% (.07) |

Table1. Simulation results for Nishi, Nakamura and clipped area

The upper part of Table 1 shows the simulation results for the Nishi and Nakamura wards. The correlation coefficients are given in the middle part. The simulation results and data in the report have the same order and are highly correlated. The bottom part of the table gives the simulation results of the clipped area; they also show a similar trend in the other cases. The values in the report are the results from a macroscopic simulation. The results of the RCRS are the aggregate values of microscopic simulation results. The experiment indicates that the RCRS results show a similar trend when conventional simulation methods are employed. Further, it shows the possibility of using ABSS in practical applications, although RCRS (in a broad sense, ABSS) requires many improvements for practical uses.

The followings are the comments provided by the local governments.

- (1) There are no applicable precedents.
- (2) There are no theoretical backgrounds, even though simulations of fire spread using the RCRS (Ver. 46) were programmed according to the Hamada models that have been used by many local governments (RoboCup Rescue).
- (3) The simulation is far from a real one, because the number of agents is small as compared to that in the real world.

These comments reveal the necessary points to practically apply ABSS, and a greater validity of the ABSS is required to persuade fire-fighting departments to use them with other methods.

AGENT-BEHAVIOR ANALYSIS BASED ON PROBABILITY MODEL

Local governments want to know the reason why one rescue plan is better than the other plans or what type of agent action would yield a good simulation result. In the real world, they can interview rescued people and ask these questions. Persons who program the agent codes explain the reasons of this difference in the simulation results. However, they are not always available after the system development is completed. Therefore, we have proposed a new method in which agent behaviors are analyzed based on probability models and the behaviors are explained in a manner that humans can accurately understand.

Agent Behavior Presentation Model

An agent's work can be formalized as follows (Weis: 2000):

$$\text{action: } S^* \rightarrow A, \text{ environment: } S \times A \rightarrow P(S),$$

where $S = \{s_1, s_2, \dots\}$ denotes the environment states, the set $A = \{a_1, a_2, \dots\}$ denotes the agent actions, and $P(S)$ denotes the power set of S . An agent plans the possible actions at s_i and executes an action a_i after which it expects to receive more rewards than the other actions. This action changes the situation to the next state. This is represented as the history of the agent $i, h_i : s_0 \xrightarrow{a^0} s_1 \xrightarrow{a^1} s_2 \dots$. The history of MAS can be represented as $H = \{h_1, \dots, h_n\}$, where n denotes the number of agents. I,

$P(S)$ indicates that stochastic processes are involved in the interactions between an agent i and the environment.

Figure 4 shows that a rescue agent comes from n_0 to extinguish two fires, namely, n_2 and n_3 . At the crossing n_1 , the rescue agent will determine which fire to extinguish and will perform an action accordingly; it will move forward, turn right, stay for a while, or something else. The next action will be selected from them by using the disaster situations and information obtained from the agent. The selection process is represented in the form of a probability modeled under the following assumptions:

Assumption 1: The agents are programmed to select their next action from the environment to efficiently reach their goal. The MAS outputs are H and the changes in the environments such as the properties of buildings in the RCRS.

Assumption 2: Agents with the same goal behave in a similar manner in similar environments.

Assumption 3: Reasonable rescue works consist of promptly searching disasters and efficiently moving to destinations. Actions that agents are supposed to take have higher probability.

From assumption 1, if the internal states of the agents cannot be observed, we assume the following assumption, which is effective for mobile agents in RCRS:

Assumption 4: Positions are related to the agent states.

For example, when the agent is at n_2 or n_3 , it extinguishes the fire. When it is at the other nodes, it performs the action involving movement. Therefore, agent behaviors are represented as a sequence of n_i . The behaviors at n_1 are described as $P_1 = \{p_{10}, p_{11}, p_{12}, p_{13}, p_{14}\}$, where p_{1j} is the probability that the agents will be at n_j at the next step. The behaviors of the agents with the same goal show a similar stochastic matrix.

Properties of F and Interpretation from Eigenvectors

For demonstrating the rescue-agent behaviors, the frequency matrix $F = \{p_{ij}\}$, where the normalization is $\sum_{ij} p_{ij} = 1$, is used instead of the stochastic matrix where the normalization is $\sum_i p_{ij} = 1$. This subsection shows

the properties of F using simple examples. A typical fire-fighter agent moves toward fires and extinguishes them till the tank becomes empty. The tank becomes empty after 10 consecutive actions involving extinguishing fires and the

fire fighter moves toward a water station at the cost of one time step. Figure 5 shows the action transitions of the fire fighter. The positions marked A indicate the initial positions of agents and those marked B and C denote the locations on fire and the water stations, respectively. Further, B represents a state in which the fire fighter extinguishes the fires and C is a state in which water is supplied.

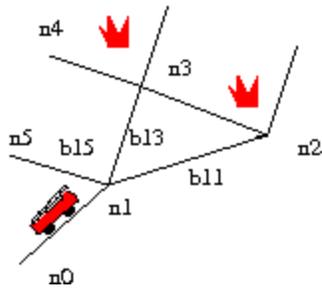


Figure 4. Model for agent motion selection

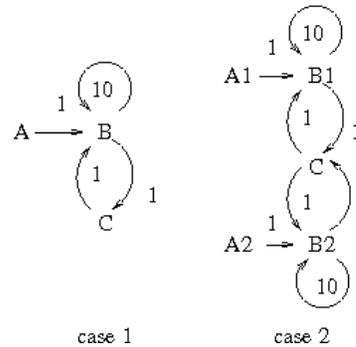


Figure 5. Pattern of rescue operations

Case 1: One fire fighter initially located at A moves toward B. The elements marked with * in the left form are nonzero. After the tasks involving extinguishing the fires and filling the tanks with water are performed n number of times, the frequency matrix becomes similar to the one shown in the middle, where $m = 1 + (10 + 1 + 1)n = 12n + 1$. The right matrix shows that the elements corresponding to the major locations remain the same after the repetition continues for a long time.

$$\begin{array}{c|ccc} & A & B & C \\ \hline A & & * & \\ B & & * & * \\ C & & * & \end{array} \xrightarrow{\text{repeat } n \text{ times}} \begin{array}{c|ccc} & A & B & C \\ \hline A & & 1/m & \\ B & & 10n/m & n/m \\ C & & n/m & \end{array} \xrightarrow{n \rightarrow \infty} F = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 10/12 & 1/12 \\ 0 & 1/12 & 0 \end{pmatrix}$$

The eigenvalues of F are 0.842 and -0.008 . The eigenvectors are $(0, -0.995, -0.09)^t$ and $(0, 0.09, -0.995)^t$. The largest-valued element of the greatest eigenvalues correspond to place B where the agent performs most of the actions.

Case 2: Fires break out at two places, B1 and B2, and two agents at A1 and A2 extinguish them separately. The left matrix corresponds to the tasks involving extinguishing the fires and filling the tanks with water n number of times and $m = 24n + 2$. The limiting operation decreases the size of the matrix; in this case, its rank becomes 3.

$$\begin{array}{c|ccccc} & A1 & A2 & B1 & B2 & C \\ \hline A1 & & & 1/m & & \\ A2 & & & & 1/m & \\ B1 & & & 10n/m & & n/m \\ B2 & & & & 10n/m & n/m \\ C & & & n/m & n/m & \end{array} \xrightarrow{n \rightarrow \infty} F = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 10/24 & 0 & 1/24 \\ 0 & 0 & 0 & 10/24 & 1/24 \\ 0 & 0 & 1/24 & 1/24 & 0 \end{pmatrix}$$

The eigenvalues of F are 0.425, 0.417, and -0.008 and the eigenvectors of the first and second eigenvalues are $(0, 0, 0.7, 0.7, 0.14)^t$, $(0, 0, 0.7, -0.7, 0)^t$. The major components of the two eigenvectors also correspond to fires B1 and B2, which are frequently visited by the agents.

An interpretation of F yields the following properties:

Property 1: F represents the agents' behavior. The rank of F is proportional to the range of the agents' movements.

Property 2: The larger elements of the dominant eigenvectors correspond to locations where the agents perform most of their actions.

Property 3: When the agents move independently, the elements of the dominant eigenvectors are separated into corresponding movements.

Applying F analysis to RCRS

The analysis using F is applied to the RCRS simulation results. In RCRS, the agents perform rescue work on the roads, crossings, and buildings, and they move from one position to another via several crossings in one simulation step. F is an $NP \times NP$ matrix, where NP is the sum of the number of roads, nodes, and buildings. M simulation steps have at the most $M - 1$ nonzero elements. When $M \ll NP$, F becomes a sparse matrix. It is convenient to use the matrix X whose elements are the nonzero elements of F .

In the RoboCup competition, the participants programmed their agents according to their rescue policies and ideas. They compete for the same disaster situations (i.e., the same initial conditions). The simulation results are open and are available at the RoboCup Rescue home page. The results of three teams $T1$, $T2$, and $T3$ during the semifinal games of RoboCup 2006 were used to verify the properties of F . The simulation was performed in 300 time steps. The Hanshin-Awaji disaster was considered to be the disaster situation; here, F is a 2322×2322 matrix and the number of fire-fighter agents is 13. Their behavior is interpreted from the eigenvalues and eigenvectors of X .

- (1) Table 2 shows that the ranks of X increase as more agents are involved. It is interesting to note that the ratio of the rank to size of the $T1$ matrix is the highest, although its size is the smallest. It indicates that the agents in $T1$ work efficiently.
- (2) The largest component of the dominant eigenvectors of $T1$, $T2$, and $T3$ correspond to the buildings indicated by black circles in Figure 6. The areas marked with black lines are places where the fires broke out initially. $T1$ and $T2$ are close to the areas affected by fires, while $T3$ is not.

The competition scores are high as the order of $T1$, $T2$, and $T3$. They explain why $T1$ is better than the other teams and where main locations are in a manner that the local government can accurately understand.



Figure 6. Main locations that correspond to the dominant eigenvectors and initial points affected by fires

DISCUSSION AND SUMMARY

MAS provides tools to solve complex problems (Jennings and S. Bussmann: 2003). To practically apply ABSS, it is required to assess the fidelity of the simulation results and explain them in a manner that people can accurately understand. The probability model has been widely used in simulations. One approach is to statistically consider the variations in the component and verify the simulation results. Johnson et al. have simulated the evacuation of public buildings and proposed risk assessment techniques (Johnson: 2006). The other approach uses a stochastic model to represent the states of the target and analyze them. The Page Ranking method used by Google represents the hyperlinked data in the Internet in a matrix-like stochastic matrix (Page: 1998).

| No. of agents used in | T1 | | T 2 | | T3 | |
|-----------------------|------|------|------|------|------|------|
| | size | rank | size | rank | size | rank |
| 1 | 90 | 80 | 60 | 48 | 76 | 63 |
| 2 | 152 | 127 | 113 | 101 | 159 | 131 |
| : | | | : | | | |
| 12 | 464 | 421 | 463 | 397 | 616 | 521 |
| 13 | 484 | 442 | 485 | 413 | 690 | 585 |
| average (R/S) | 0.88 | | 0.86 | | 0.84 | |
| Std. (R/S) | 0.03 | | 0.02 | | 0.01 | |

Table 2 X's size and rank

We propose that a method to independently evaluate the agents' behavior in tasks will be one of the key issues in applying MAS to social tasks. In this paper,

- (1) We first discuss the need of agent-based disaster and rescue simulation systems for use by local governments.
- (2) Next, we show that the simulation results are comparable to other conventional methods. Experiments using actual GIS are highly correlated with the other methods. It reveals the possibility of practically applying ABSS.
- (3) Last, we propose a method to present the agent behaviors using a probability model and interpret them using the eigenvalues of the stochastic matrix. A task-independent method is applied to the RCRS results. It yields a good interpretation of the agents' behaviors.

In the future, various knowledge or tactics of real agents will be implemented in software agents when the ABSS approach will be practically used. The proposed method will provide a tool to compare the knowledge and tactics that can be implemented in agents. In such cases, they will support decision making. We expect that the discussions and our proposed method will assist in the investigation of future research topics in developing disaster simulations.

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REFERENCES

1. N. R. Jennings, K. Sycara, and M. Wooldridge. (1998) A roadmap of agent research and development. *Autonomous Agents and Multi-Agent Systems*,1:275–306
2. NLI. (1998) Report on seismic assumed damage (Japanese). Non-Life Insurance Rating Organization of Japan
3. H. Kitano, S. Tadokoro, I. Noda, H. Matsubara, T. Takahashi, A. Shinjou, and S. Shimada. (1999) RoboCup Rescue: Search and rescue in large-scale disasters as a domain for autonomous agents research. In *IEEE International Conference on System, Man, and Cybernetics*, pp. VI-739 - VI.743
4. RoboCup Rescue: <http://www.robocuprescue.org/>
(fire spread simulation): www.informatik.uni-freiburg.de/~brenner/Publications/nuessle-et-al-robocup2004.pdf
5. T. Takahashi. (2006) Requirements to agent-based disaster simulations from local government usage, *Proc. First International Workshop on Agent Technology for Disaster Management, aamas-06*, pp. 78–84
6. G. Weiss. (2000) *Multiagent Systems*. The MIT Press
7. N. R. Jennings and S. Bussmann. (2003) Agent-based control systems. *IEEE Control System Magazine*
8. C. W. Johnson.(2006) The Application of Computational Models for the Simulation of Large Scale Evacuations Following Infrastructure Failures and Terrorist Incidents, *Proc. NATO Research Workshop on Computational Models of Risk to Infrastructure*, 9–13 May 2006
9. L. Page, S. Brin, R. Motwani, and T Winograd. (1998) The page rank citation ranking: Bringing order to the Web. <http://www-db.stanford.edu/backrub/pageranksub.ps>