Resilience Analysis of Critical Infrastructure

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Abstract: - Critical infrastructure is the basis of our modern life, and the resilience of critical infrastructure is a serious issue for maintaining our safe and secure society. After several remarkable events like terroristsô attack in US in 2001 and the Great East Japan Earthquake in 2012, a shared recognition that more comprehensive approaches for crisis management is necessary. For resilience enhancement of critical infrastructure, we have to understand the response of critical infrastructure to a crisis. Computer simulation is a promising approach for this purpose, but how to model interdependencies that exist among different sectors of infrastructure is a problem to be solved in resilience analysis of critical infrastructure using simulation. From this background, a modeling and simulation method of critical infrastructure considering interdependencies among different sectors were developed. The system consists of detailed models for separate sectors, and the integrated model including multiple sectors of critical infrastructure. The modeled sectors include electricity, gas, water supply, roads, and telephone networks in the metropolitan area of Tokyo. Sensitivity studies were conducted based on the 4R framework of resilience to examine the functionality of the simulation system. Finally, it has been shown that a human-centered viewpoint is essential for assessing the resilience of critical infrastructure.

Key-Words: - critical infrastructure, lifeline, resilience, interdependency analysis, service system, socio-technical systems, computer simulation

1 Introduction

Critical infrastructure, which consists of a multiple sectors such as power grids, water supply, energy supply, transportation, telecommunication, and so on, is the basis of our modern life. Loss of its function therefore is a crucial threat to the modern society, and the resilience of critical infrastructure is a serious issue for every country. After the terroristsô attack in US on September 11th, 2001, in particular, preparedness against all hazards including not only natural disasters but also intentional incidents have attracted interests of both practitioners and researchers. In Japan, the Great East Japan Earthquake and the Fukushima-Daiichi Nuclear Power Plant Accident in 2012 evoked a shared recognition that more comprehensive approaches for crisis management is necessary. Consequently, the Basic Act for National Resilience was enacted in

2013, and Japanese government is now promoting the National Resilience Policy for enhancing national resilience of Japan [1][2].

For resilience enhancement of critical infrastructure, we have to understand the response of critical infrastructure to a crisis. Computer simulation is a promising approach for this purpose, but how to model interdependencies that exist among different sectors of infrastructure is a problem to be solved in resilience analysis of critical infrastructure using simulation. We are now developing a method to identify which part is vulnerable and what risk exists by simulating complex behaviors of critical infrastructures under various threat scenarios considering their interdependencies [3]. We expect the project will contribute to the crisis management policy of Japan, presenting options for the risk governance strategy referring to the outcomes of technological analysis. This paper, however, will focus on technological aspects of the project and present the modeling architecture of simulation as well as preliminary results.

2 Simulation Model

Our research group is developing a model of the critical infrastructure including the power grid, gas supply network, water supply network, road transportation network, and telecommunication network in the metropolitan area of Tokyo, considering interdependencies and developing a system for simulating its complex behaviors under various threat scenarios. The system consists of detailed models for separate sectors, and the integrated model including all of them.

2.1 Integrated Model

In the conventional approach of interdependency analysis of critical infrastructure, only the facilities of infrastructure, lifelines, are modeled. From a viewpoint of socio-technical context, however, this approach is insufficient and services that are provided relying on the critical infrastructure should be considered. It is because what are worthwhile for the people are services like commodity supply, medical service, administration, finance service, and so on, which are provided relying on these facilities. Operations of lifelines are also services. Since the value of these services depends on civic life, the resilience of service systems is further interdependent with civic life.

From the above consideration, we have proposed a socio-technical model shown in Fig. 1 as the integrated model of critical infrastructure [4]. This model consists of three subsystems of lifelines, services, and daily life. Each lifeline system is represented as a network. Each node represents some facility and each link represents a conduit or supply line of resource. The whole model of lifelines is a multi-layered combination of multiple networks.

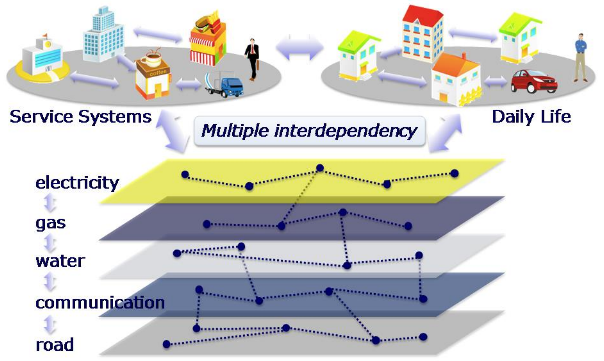

Fig. 1. Integrated model of critical infrastructure

Provision of services, daily life, and recovery of lifeline systems are modeled by the agent based modeling architecture. A service agent is the provider of a service and it is defined by the company, organization, task, supplier, service type, and so on. A citizen agent carries out various activities in civic life like reception of services, watching and listening of mass media, taking a bath, dining, shopping, and so on. It is defined by the attributes representing residence, family, and member. Different lifestyles are distinguished between different types of a citizen agent. A recovery agent repairs damaged lifeline systems. A recovery team is organized by recovery agents and it is attributed with the ratio of assembly, the ratio of resource sufficiency, the capability of field communication, and so on.

When analyzing the resilience of multiple sectors of critical infrastructure, it is essential to consider their interdependencies. If power supply has been lost, for instance, water supply does not work either due to pump shutdown, and road transportation will be confused due to blackout of traffic signals. If road transportation is confused, repair of the damaged power grid facility will delay. The influence of local damage in a single sector will propagate not only over the same sector but also over other sectors. It may cause a cascading failure of the whole critical infrastructure. From this concern, studies on interdependency analysis of

Table 1. Multiple interdependencies

	Lifeline	Service	Life
Lifeline	Between Lifelines • Physical • Functional • Resource • Alternative	Service on Lifeline • Functional • Resource • Transportation	Life on Lifeline • Functional • Resource • Transportation
Service	Lifeline on Service • Recovery	Between Services • PCANS: Agent-Task-Resource • Alternative	Life on Service • Demand and supply • Satisfaction
Life	Lifeline on Life • Demand and supply	Service on Life • Demand and supply • Labor supply	Between Lives • Resource sharing and allocation

critical infrastructure have been continued in US and Europe particularly after the terroristsô attack in 2001 [5][6].

If critical infrastructure is modeled including service and daily life as shown in Fig. 1, it is necessary to consider interdependencies between different subsystems of lifelines, services, and daily life. The interdependencies between these three subsystems are summarized in Table 1. Thare are interdipendencies of service on lifeline, for instance, that lifeline provides resources necessary for service and transportation for service providers. Lifeline is dependent on service in a way that damages of lifeline facilities will be repaired by the recovery service.

The interdependencies in terms of services can be classified into two classes, intra- and inter-organizational ones. The former is represented as a PCANS model and the latter as an Integrated Organization (IO) model in this study [7][8]. Fig 2 show an overview of the organization model of services proposed in this work.

In PCANS model, an organization is described as a triplet of individual, task, and resource. There are five relations between these three elements, PCANS: Precedence, Commitment of resources, Assignment of individuals to tasks, Networks of relations among personnel, and Skills linking individuals to resources. Precedence is a sequential order between different tasks, that some other tasks should have been done before starting a particular task. Commitment of resources describes what resources are required for execution of a particular task. Assignment of individuals to tasks show who are in charge of carrying out a particular task. Networks of relations among personnel defines the structure of organization. Finally personal skills will affect the amount and the class of resources required for execution of a particular task.

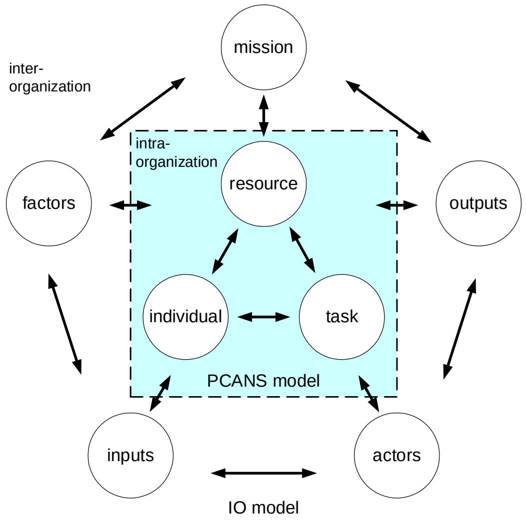

Fig. 2 Organization model of services

The Integrated Organisation (IO) model describes the interactions of an organization with the outside environment, and it is described by the following items. Outputs are services that the organization produces, and inputs are the resources that the organization consumes for the service production. Actors are agents of verious types: service suppliers, consummers, collaborators, pompetetors, and so on. Mission gives the organization the reason for existing. Factors describe political, economical, technical, social, or cultural conditions that affect organizational behaviour.

2.2 Power Grid Model

In addition to the integrated model of critical infrastructure, we are developing separate models for each infrastructure sector. A model of the power grid around the metropolitan area of Tokyo, Kanto, has been constructed as shown in Fig. 3 considering the present siting of power plants in the area and using single point approximation for the power grids of the surrounding areas.

The risk of the power grid in an emergency such as an earthquake is evaluated by probabilistic planning by minimizing the total cost, which is the sum of the facility cost and the expected variable cost for various risk scenarios [9]. This method enables us to obtain the best energy mix in the metropolitan area of Tokyo considering the shutdown risk of the power plants concentrated around Tokyo Bay as well as the damage risk of the transmission lines.

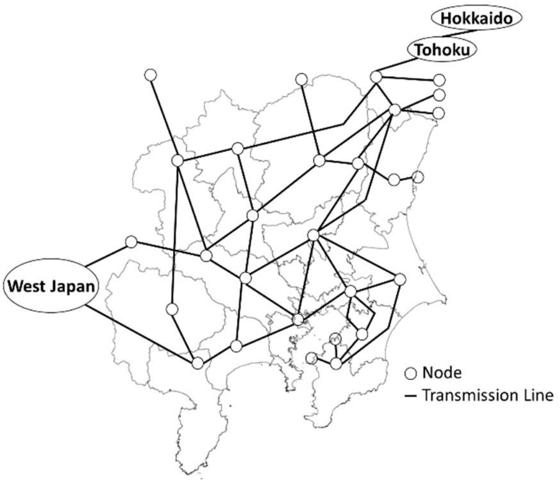

Fig. 3. Power grid model of Kanto

Referring to the annual probability of earthquake that directly hits Tokyo area, preliminary assessment was done for four scenarios of 0%, 1%, 3%, and 5% risk. Fig. 4 show an example of optimized energy mix in a day after a seismic disaster.

As a result of the analysis, the following findings were obtained. As the earthquake probability increases, (1) new construction sites of combined natural gas plants shift from Tokyo Bay Area to the other areas, (2) the capacity of private power generation newly introduced increases, (3) the capacity of storage batteries introduced around Tokyo Bay Area increases. This result suggests that these decisions are useful for enhancing the robustness of the power grid in this area from an economic viewpoint. If the value of earthquake risk officially published by the government is correct, half of the expected combined natural gas plants should be built in the peripheral area of Tokyo rather than around Tokyo Bay. This example demonstrates that the developed method provides useful insights for decision-making in national security policy.

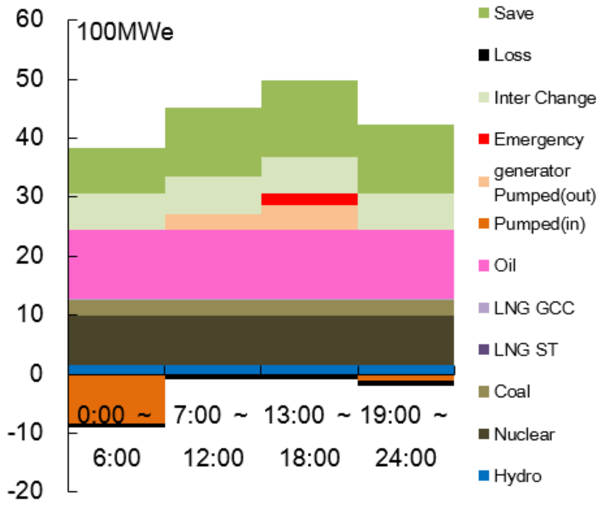

Fig. 4 Optimum energy mix after seismic disaster

2.3 Road Network Model

A precise road network model of the metropolitan area of Tokyo was constructed in a format of Multi-agent-based Traffic Simulator, MATES. MATES is a multi-agent traffic flow simulator, which can simulate the motion of each car along the road network considering various interactions between cars as well as cars and the traffic environment [10]. The road network model describes the topology of road network, the number of lanes of each road segment, the structure of crosses, and so on, which are required to perform traffic simulation at a microscopic level.

In order to apply MATES simulation to the road network model of a realistic scale, speeding-up of simulation was attempted. Keeping the preliminary data on road structure that are referred to frequently during simulation reduced the computation time less than one third. Since the path search algorithm was the bottle neck for fast simulation, a hierarchical path search technique has been adopted, where travel paths are searched for using a simplified road network model and then using a precise one. This improvement contributed to cutting 98% of the computing time for travel search.

The parallel computing technique that we developed with virtual road network models was applied to the realistic model of Tokyo and the efficiency of parallel computing was evaluated. Fig. 5 shows an example of the evaluation. Model1, 2, and 3 are virtual models and the model size is in the order of Model2 < Model1 < Model3. As the model size increases, the efficiency of parallel computing increases, but this performance does not hold for the model of Tokyo. Close investigation of this performance revealed that a large difference in the road density between different segmentation zones resulted in failure in balancing computational loads among many processors and then it caused the poor performance in parallel computation. Now we are implementing a new scheme of zone segmentation that reflects difference in road density.

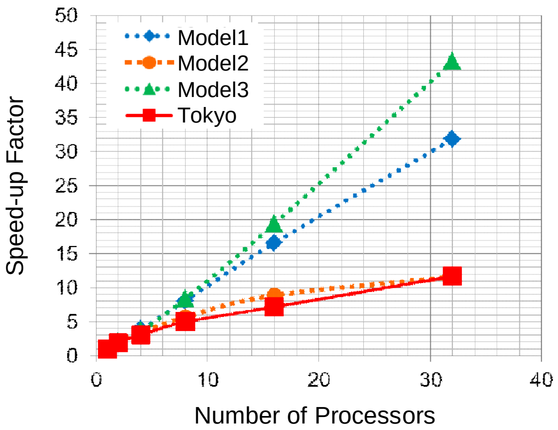

Fig. 5. Efficiency of parallel computing

2.4 Water Supply Network Model

Since water supply tubes are installed along the primary roads, the water supply network of the metropolitan area of Tokyo was constructed from the road network model for MATES. In addition, the parts of network where seismic reinforcement work has already been completed were presumed. The locations of 2,659 critical facilities such as police offices, fire stations, large hospitals, and so on were identified referring to the open database of Ministry of Land, Infrastructure, Transport, and Tourism. It is assumed then that the region between each critical facility and the nearest water supply point is seismically resistant. Fig. 6 shows the water supply network model of Tokyo with the locations of critical facilities.

The damage of this network expected after a great earthquake that directly hits Tokyo was estimated by the square grid of 500m using the formula for damage estimation already proposed. The maximum seismic acceleration of 80 cm/sec and the liquefaction factors estimated and opened by Tokyo Metropolitan Government were used for this estimation. It is revealed consequently that the damage is greater in the east area than the west area of Tokyo, because it is almost determined by the liquefaction factor except the regions where seismic reinforcement has been completed.

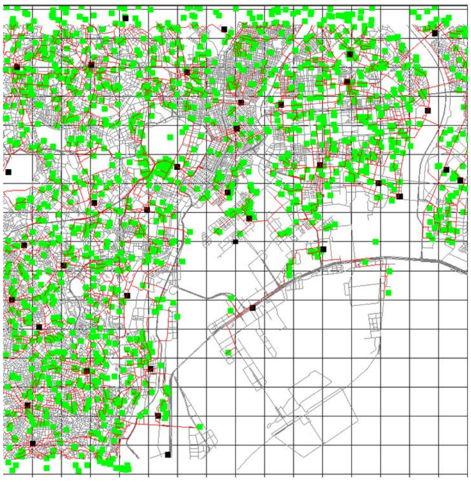

Fig. 6. Water supply network model of Tokyo

2.4 Telecommunication Network Model

A telecommunication network model was developed using the data opened from NTT East Company. The logical topology of the telecommunication network has a three-layered hierarchy that consists of regional, local, and customer relay stations from the top to the bottom, and it contains one regional, three local, and 102 customer relay stations within the target area of modeling. A regional or local relay station shares the same building with some customer relay station. It is assumed for simplicity that all these relay stations are connected physically in a single optical communication ring.

Based on the traffic theory, a simulation system was developed for evaluating the call loss probability using the following algorithm.

(1) Initialize the number of lines between nodes.
(2) Generate a call.
(3) Determine the holding time of the call.
(4) Determine the routing of communication.
(5) Determine success or failure of the call.
(6) Terminate the calls that end immediately.
(7) Evaluate the call loss probability.
(8) Repeat from (2) till the end of simulation.

The call loss probability evaluated by this simulation under an overloading condition of communication demands agreed well with the value evaluated theoretically by Erlang-B formula as shown in Fig. 7. In the next stage, each connection in the physical ring was destroyed and the call loss probability was evaluated for a surge of ten times communication demands after crisis. Fig. 8 shows the result of this simulation as a hazard map. It is shown here that the links located around the cover area boundary of different local relay stations are relatively resistant against damage.

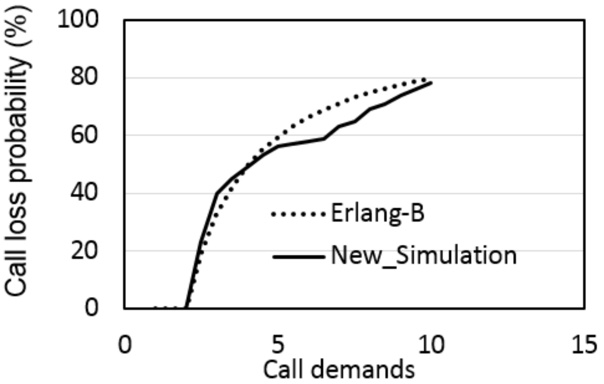

Fig. 7 Call dends and call loss probability

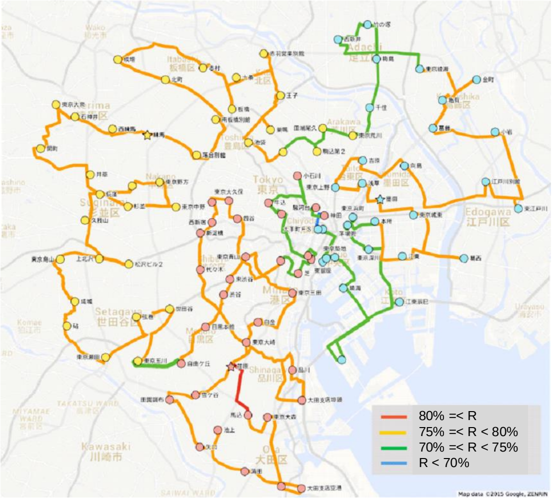

Fig. 8. Call loss probability with damaged link

3 Assessment of Resilience

The resilience of critical infrastructure that was damaged by some event like natural disaster depends on the recovery plan of lifelines. In the past disasters, the lifeline operators in each sector made their best efforts to recover their own facilities as soon as possible, but they made no attempt to optimize the recovery plan considering interdependencies between different lifelines. Interdependency analysis is a key to mitigate this drawback, but the studies of interdependency analysis so far have ignored services and civic life. We try to globally optimize the recovery plan considering these important factors.

We adopted Genetic Algorithm (GA) in this research to optimize the recovery plan, while studying more decentralized and opportunistic planning method. A recovery plan, which recovery team covers which damaged part of the lifeline systems in what order, is coded as a genome and a population of genomes evolves by genetic operations of natural selection, cross over, and mutation under some fitness function. The recovery plan is optimized by this process.

The next fitness function was adopted.

$$F = \alpha Rr + \beta Sa + \gamma Cs \text{ ï } \delta Rc \qquad (1)$$

Rr, Sa, Cs, and Rc are the recovery ratio of infrastructure facilities, the relative achievement level of services, the satisfaction level of the citizens, and the recovery cost. Parameter α, β, γ, and δ are importance weight of each contribution. The recovery cost is a combination of the total migration length, the total work hours, and the total migration cost over the all recovery teams.

The effectiveness of the approach was demonstrated using a virtual lifeline model of 6x6 square grid shown in Fig. 9 and test scenarios. Lifelines of 12 types and 550 agents were considered in this test simulation. The sum of Sa and Cs in Equation (1) was used as the measure of system performance.

Fig. 10 compares two recovery curves obtained considering just the recovery ratio and all the four factors in Equation (1). In terms of service achievement and citizensô satisfaction, the fitness function including all of the four factors gave a better result than the conventional approach. It shows that the comprehensive infrastructure model of this study, which consider not only lifeline facilities but also services and civic life, is useful for evaluating the resilience of critical infrastructure from a human-centered viewpoint.

It is impossible to validate simulation models of this type based on empirical data. We performed therefore sensitivity analysis to check behavior of the simulation model. Some model or scenario parameters were changed that correspond to the R4 framework of resilience: robustness, redundancy, resourcefulness, and rapidity [11]. Fig. 11 shows an

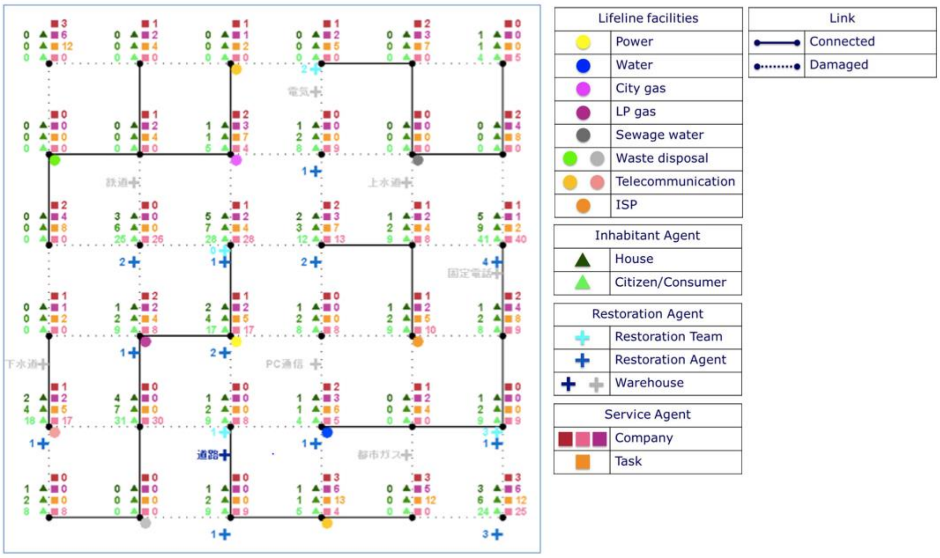

Fig. 9 Schematic view of the virtual inftrastracture network for test simulation

example of the results, which shows the area of resilience triangle for various scale of damage. The area of resilience triangle [11], which is the area between the performance curve degraded after a crisis and the normal level of performance, is often used as a metric of systems resilience. It shows the sensitivity of the resilience to the robustness of the system; when the robustness gets low, the resilience degrades. Such a reasonable response indicates qualitatively that the model is functional for evaluating the resilience of this system.

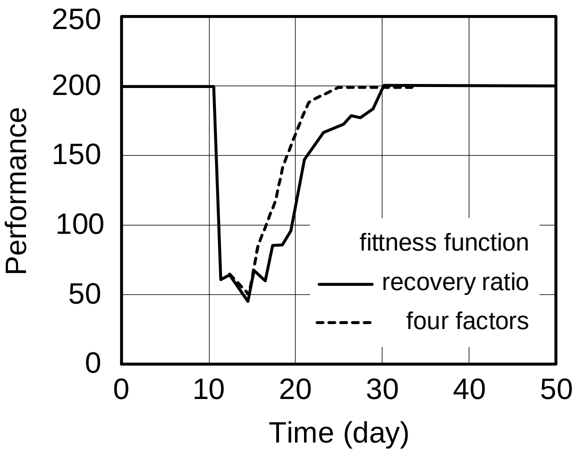

Fig. 10. Impact of services and civic life

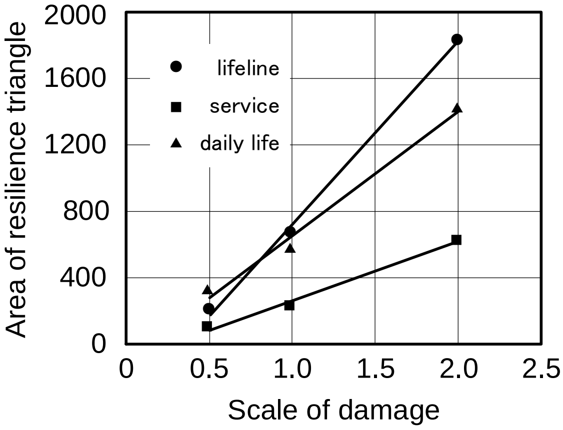

Fig. 11. Sensitivity of resilience to robustness

4 Conclusion

The resilience of critical infrastructure is a key issue for maintaining our safe and secure society, because it is the basis of our modern life. For resilience enhancement of critical infrastructure, predicting and understanding its response of critical infrastructure to a crisis are required, and how to model interdependencies among different sectors of infrastructure is a problem to be solved. This paper discussed how to model these interdependencies and how to assess the resilience of multiple lifelines of critical infrastructure. Our models consist of the integrated and separate models for multiple sectors of infrastructure. The integrated model includes not only lifeline systems but also service and civic life systems as subsystems. We can thereby simulate the response of critical infrastructure more realistically under a socio-technical context. Test simulation using a virtual structure of the lifeline networks demonstrated that considering service and civic life is necessary to evaluate the resilience of critical infrastructure from a human-centered viewpoint. Models were presented for the power grid, road network, water supply network, and telecommunication network of the metropolitan area of Tokyo. We are now trying to expand the integrated model also for applying it to the metropolitan area of Tokyo. It is expected this approach can provide technical insights useful for decision makers in the emergence response policy.

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