Optimization of disaster restoration plan for water supply system using a high-fidelity restoration process simulation and genetic algorithm

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Abstract: Post-disaster restoration planning for a water supply system is crucial to support human life and various social activities. However, optimizing restoration plans for damaged lifeline infrastructure such as the water supply system is not straightforward. One of the major reasons for this problem is that there is no well-established methodology and consensus for determining the priority or objective function for creating an optimal restoration plan. Therefore, we are currently developing a high-fidelity water supply restoration process simulation based on our previously developed modeling framework for urban sociotechnical systems, which consists of three subsystems: lifeline infrastructures, industry, and civil life. This simulation incorporates a restoration plan optimization method using a genetic algorithm (GA), and it can provide and compare optimal restoration processes under various objective functions. This paper presents the modeling of the water supply system and some simulation results, along with discussions on practical disaster response and preparedness decision-making support for an actual local city.

Keywords: Disaster Restoration Plan, Water Supply System, Genetic Algorithm (GA)

1. INTRODUCTION

Post-disaster restoration planning for a water supply system is crucial to support human life and various social activities. However, optimizing restoration plans for damaged lifeline infrastructure such as the water supply system is not straightforward. One of the major reasons for this problem is poor situation awareness owing to the dynamic changes and uncertainty during disasters [1,2]. However, this problem is only a technical one, and it can be solved by supporting shared situation awareness through real-time monitoring using satellites and drones and information communication technology (ICT) systems to share monitoring data and information [3]. Another major reason is a sociotechnical problem in that there is no well-established methodology and consensus for determining a priority or objective function for optimizing restoration plans.

Considering this background, we are currently developing a high-fidelity water supply system restoration process simulation that incorporates a restoration plan optimization method based on a genetic algorithm (GA). To deal with the sociotechnical aspects of this problem, the simulation model is based on a previously developed modeling framework that can consider various social activities and multiple interdependencies underlying urban systems [4]. In this modeling framework, an urban system is modeled as a system of systems consisting of three subsystems—lifeline infrastructures, industry, and civil life—and the interactions and interdependencies among them. The restoration process and various social activities are implemented using a network model and an agent-based model. The network model describes the configurations of the lifeline infrastructures, including the water supply system and road network. The agent-based model describes various activities of different types of agents such as citizens, repair squads, industrial companies, and lifeline facilities.

2. MODELING FRAMEWORK

In our previous study, we proposed a modeling framework for urban sociotechnical systems [4]. This modeling framework employs a system of systems approach; it consists of three subsystems including lifeline infrastructures, industry, and civil life as well as the interactions among them. This section presents an outline of this modeling framework.

2.1 Multiple Interdependencies Model

There are physical and functional interdependencies among infrastructures such as water supply systems and road and electricity networks; if one function of the infrastructure is damaged by a disaster, it has an effect that propagates to other infrastructures. This effect also propagates to daily life and economy [5,6]. Therefore, these multiple interdependencies cannot be ignored when we consider disaster prevention and restoration. As stated above, our previously proposed urban sociotechnical system modeling framework employs a system of systems approach and consists of three subsystems—lifeline infrastructures, industry, and civil life as well as the interactions among them. This modeling framework captures these three subsystems and their nine types of interdependencies, as listed in Table 1.

Table 1: Subsystems and Interdependencies of Modeling Framework

		On		
		Civil Life	**Industry**	**Lifeline**
Dependent	**Civil Life**	1) Between civil life ● Means-ends ● Resource conflict ● Geographical	2) Civil life on industry ● Supply ● Geographical	3) Civil life on lifeline ● Supply ● Geographical
	Industry	4) Industry on civil life ● (Labor) Supply ● Geographical	5) Between industry ● Supply ● Demand ● Alternative ● Geographical	6) Industry on lifeline ● Supply ● Geographical
	Lifeline	7) Lifeline on civil life ● Demand ● (Labor) Supply ● Geographical	8) Lifeline on industry ● Demand ● Supply ● Geographical	9) Between lifeline ● Supply ● Demand ● Alternative ● Geographical

3. SIMULATION MODEL

This section explains how the simulation model of each subsystem of urban sociotechnical systems is built for disaster recovery simulation. Based on the modeling framework, each subsystem as well as the multiple interdependencies were modeled and implemented using the agent-based model incorporated with the network model.

3.1. Lifeline Model

Urban areas include various lifeline infrastructures such as the power grid, water supply, city gas, road, and railroad. Such lifeline infrastructures are implemented as a network using a network model with links and nodes. A link such as an electric power cable, water pipeline, or road represents a connection between lifeline infrastructures, and it has parameters representing length, type (e.g., material, diameter, function, etc.), and extent of disaster damage. A node such as a water junction or road intersection represents a connection point of links. Lifeline facilities such as water distribution reservoirs or power substations are represented by the agent model and are placed on and associated with a link. Other types of agents, such as companies and citizens, are also located on and associated with links. The availability of lifeline resources and functions is determined by the reachability to the links of the lifeline facilities.

3.2. Industry Model

Industrial companies play an important post-disaster role in the economy by providing various products and services that are necessary for the recovery of daily life and the economy of a city. An industrial company and a worker are implemented by an agent-based model. The industrial activity of each company agent is represented by various production functions that describe the input-output relations of resources and output products. A worker agent is a mobile agent that commutes from his/her house to the company through nondamaged roads and becomes a part of the labor force at his/her company.

3.3. Citizen Model

People perform daily activities such as eating and drinking, laundry, bathing, and shopping. They try to continue these activities after a disaster if possible. If all or some of these activities are not possible, their quality of life, used below as one of the factors of the objective function for the optimization, is considered to have deteriorated. A citizen and their daily activities are modeled and implemented using an agent-based model.

3.4. Restoration Model

Once lifeline systems are damaged by disasters, it is necessary to restore them. If the damage is large and widely distributed, the order of restoration becomes critical because it affects the speed of total recovery of the city, including its economy and quality of life. Restoration is performed by restoration squads (workers) that are implemented using an agent-based model. Restoration worker-agents gather at the location of the squad from their houses, obtain the necessary resources from the warehouse, and then repair disaster-affected lifeline links according to their restoration plan.

3.5 Disaster Recovery Simulation

By using the above models, we developed a disaster recovery process simulation for damage recovery of a water supply system. First, disaster damage to the lifeline links of the water supply system is set as the initial condition of the simulation. Then, when the simulation starts, restoration agents begin to repair the affected lifeline links according to their restoration plan, and companies and citizens respectively conduct their production and daily life activities if possible.

4. TARGET CITY MODEL

Because the final goal of this study is to apply this simulation to practical decision-making support for a municipal government to aid disaster response and preparedness, we built a simulation model by referring to the actual data of a target city, such as population and its distribution, number of business establishments and its distribution, and geographical topology of lifeline networks. In addition, we developed a restoration process model for the water supply system with the aid of subject matter experts and set model parameters to reflect real situations.

The target city in this study is Arao City, Japan, with a population of approximately 50,000 people. Only the central part of the target city was modeled for the simulation as it contains well-constructed water supply networks, a few residential quarters, and an industrial district.

4.1. Lifeline Networks

Two lifeline networks, a water supply network and a road network, were considered in this simulation. Water supply networks are modeled based on the actual geographical information of water pipelines, such as the location of water reservoir facilities and pipelines. Each pipeline has parameters such as its diameter and material. We defined six types of pipes in terms of the combinations of diameters and materials. Water pipelines are usually laid underground along major roads; thus, networks with the same topology are used for road networks. Figure 1 shows the water supply network and road network. In Figure 1, the line beside the asterisk "*" indicates the location of the water distribution reservoir.

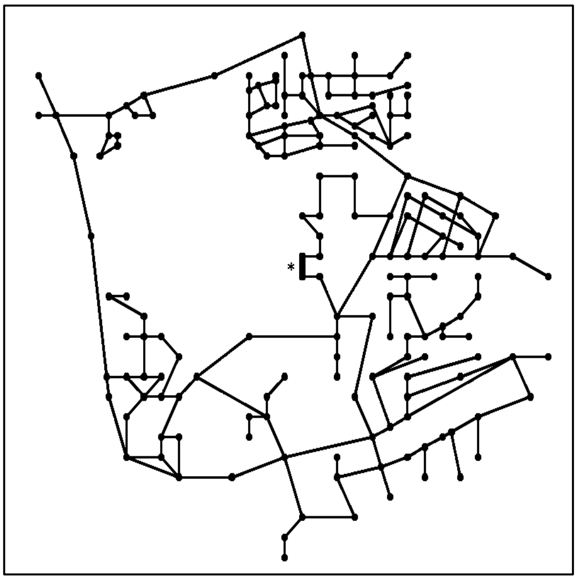

Figure 1: Water Supply and Road Lifeline Networks

4.2. Industry and Citizen

Companies and citizens are placed at links in reference to open data of public statistics of population and industry. To consider the different degrees of dependencies of company activities on water, we introduced the "degree of dependency of water supply," which is represented by $\boldsymbol{\omega_i}$ in Equation (3), into the company model. For example, some companies such as business offices are less dependent on water supply because they use water only for toilets and hand-washing. These companies are assigned a lower degree of dependency. On the other hand, others such as hospitals and food factories use larger amounts of water and are assigned a higher dependency. Economic losses due to unavailability of water supply are calculated by considering the degree of dependency.

We also introduced the "degree of preference of water" to the citizen model to consider the different impacts of water loss on daily activities. For example, people who like taking a bath or people who are tending to the sick are more likely to be affected if they cannot use water. Loss of quality of life due to unavailability of water supply is calculated by considering such preferences, which are represented by $\boldsymbol{Needs_i}$ in Equation (4) in the next section.

4.3. Damage Estimation

We estimated the potential earthquake damage to the water pipeline in the target area by using the damage prediction formula [7] and found that the damage was concentrated in pipes smaller than 100φ in diameter. Based on this estimation, we assumed that 40 pipes smaller than 100φ in diameter (pipeline types 2–6) would be damaged in random places. Figure 2 shows the initial setting of the water supply network in which damaged pipes are represented by dashed lines. Table 2 shows the number of damaged pipes according to their types.

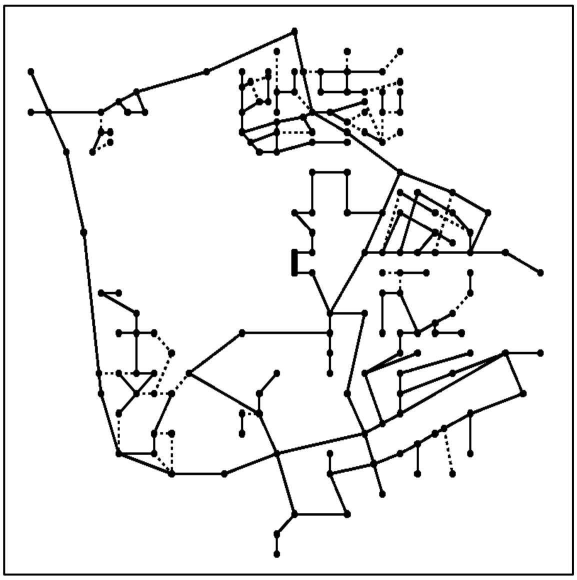

Figure 2: Damaged Networks (Dashed lines)

Table 2: Damage to Pipes in Scenario

Pipeline Type	Number of Damaged Pipes (Total Number of Pipes)
1	0 (66)
2	20 (28)
3	14 (31)
4	2 (29)
5	2 (20)
6	2 (25)

4.4 Restoration and Support

There are six restoration companies (i.e., six squads) for the water supply system in the target area, and they can repair one pipe per day. We assumed that only 20 of the 40 resources initially needed for the restoration are available in the warehouse and that these can be used only 12 h after a disaster because of preparation and movement. The remaining 20 resources are received as support from outside the city. Table 3 shows the assumed resources comprising support received from outside the city.

Table 3: Outside Resources in Scenario

	Resource Type (Pipeline Type)						Squads	Arrival Time
	1	2	3	4	5	6		
Target Area	0	10	7	1	1	1	6	12
City A	0	2	4	0	0	0	1	30
City B	0	2	1	0	0	0	1	36
City C	0	2	0	1	0	0	1	36
City D	0	2	0	0	1	0	2	36
City E	0	2	2	0	0	1	2	36

5. OPTIMIZATION OF RESTORATION PLAN USING GENETIC ALGORITHM

A GA [8] was used for optimizing the restoration process in the recovery simulation. GA is a stochastic optimization method that imitates biological evolution by implementing operators such as selection, crossover, and mutation. Each chromosome of the GA represents the restoration plan of the lifeline network and describes the order of restoration for damaged pipelines. In this simulation, Equation (1) was used to calculate the objective function of the GA.

$$\boldsymbol{Objective\ Function} = \boldsymbol{\alpha} \times \boldsymbol{fitness_L} + \boldsymbol{\beta} \times \boldsymbol{fitness_I} + \boldsymbol{\gamma} \times \boldsymbol{fitness_C} \quad (1)$$

In Equation (1), $\boldsymbol{fitness_L}$, $\boldsymbol{fitness_I}$, and $\boldsymbol{fitness_C}$ are the fitness values of the three subsystems of the city; these values are respectively calculated using Equations (2), (3), and (4) below. Furthermore, $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and $\boldsymbol{\gamma}$ are the respective weight coefficients of these three values, and they determine the priority of subsystems in the restoration process.

$$\boldsymbol{fitness_L} = \sum_{day} \left(\sum_{i} |\boldsymbol{A_{i,day}}| \,/ \sum_{i} |\boldsymbol{A_i^{normal}}| \right) \quad (2)$$

$$\boldsymbol{fitness_I} = \sum_{day} \left(\sum_{i} (\boldsymbol{\omega_i} \cdot \boldsymbol{\delta_i}) \,/ \sum_{i} \boldsymbol{\omega_i} \right)$$
$$\begin{cases} \boldsymbol{\delta_i = 1} \ \ (\boldsymbol{if\ B_i\ is\ available}) \\ \quad \boldsymbol{\delta_i = 0} \ \ (\boldsymbol{otherwise}) \end{cases} \quad (3)$$

$$\boldsymbol{fitness_C} = \sum_{day} \sum_{n} \left(\boldsymbol{QOL_{n,day}} / \boldsymbol{QOL_{n,day}^{max}} \right)$$
$$\boldsymbol{QOL_{n,day}^{max}} = \sum_{i} \boldsymbol{Needs_{i,n}(day)} \quad (4)$$

$\boldsymbol{fitness_L}$ is the sum of the recovery ratio of the water supply network. $\boldsymbol{A_i}$ is the number of available links reachable to the water distribution reservoir through links without damage, and $\boldsymbol{A^{normal}}$ is the total number of links.

$\boldsymbol{fitness_I}$ is the degree of task achievement of all companies. $\boldsymbol{B_i}$ is the number of tasks completed by company i, and $\boldsymbol{B^{normal}}$ is the number of all tasks in company i. In this study, each company agent has only one task for simplification. $\boldsymbol{\omega_i}(= \boldsymbol{1, 3, 7})$ is the weighting factor for task $\boldsymbol{B_i}$ that represents the importance of water supply for the task execution.

$\boldsymbol{fitness_C}$ is the total degree of satisfaction, and it is defined by the quality of life (QOL). In this study, each citizen agent has two daily activities for simplification. One is an activity needing water and the other is an activity not needing water. $\boldsymbol{Needs_i}(= \boldsymbol{1, 3, 7})$ is the weighting factor for the former type of activity.

6. SIMULATION RESULTS

We simulated and optimized the recovery process of the target city. Table 4 shows the parameter settings used for the simulation. The total simulation period is 30 steps corresponding to 30 days, and the initial damage is assigned at day 10. The probabilities for selection, crossover, and mutation in GA are 0.5, 0.3, and 0.1, respectively.

Table 4: Parameter Settings used in Simulation

Lifeline Networks	
Nodes	173
Links	199
Damaged Links	40
Types of Pipeline	6
Industry and Citizen	
Companies	153
Residences	257
Citizens (Workers)	1540
Time Step	
Simulation Days	30
Disaster Occurrence Date	10
Agent's Active Hours Per Day	12
GA Settings	
Population	100
Generations	10000
Selection Rate	0.5
Crossover Rate	0.3
Mutation Rate	0.1

6.1 Restoration Plan Optimization

Figure 3 shows the optimization process of the GA over the specified number of generations. The horizontal axis represents the number of generations of the GA and the vertical axis, the fitness value calculated using Equation (1). The graph shows that the fitness value rapidly increases over the first 400 generations, then increases incrementally, and finally converges at approximately 6000 generations. This result indicates that the GA optimization works appropriately.

Figure 4 shows the recovery curve of the water supply system obtained under a randomly created restoration plan (nonoptimized) and the optimized restoration plan obtained using the GA. The horizontal axis represents the simulation time step (day) and the vertical axis, the ratio of availability of water supply in the target area. The graph shows that restoration duration under the optimized plan was 5 days shorter than that under random restoration.

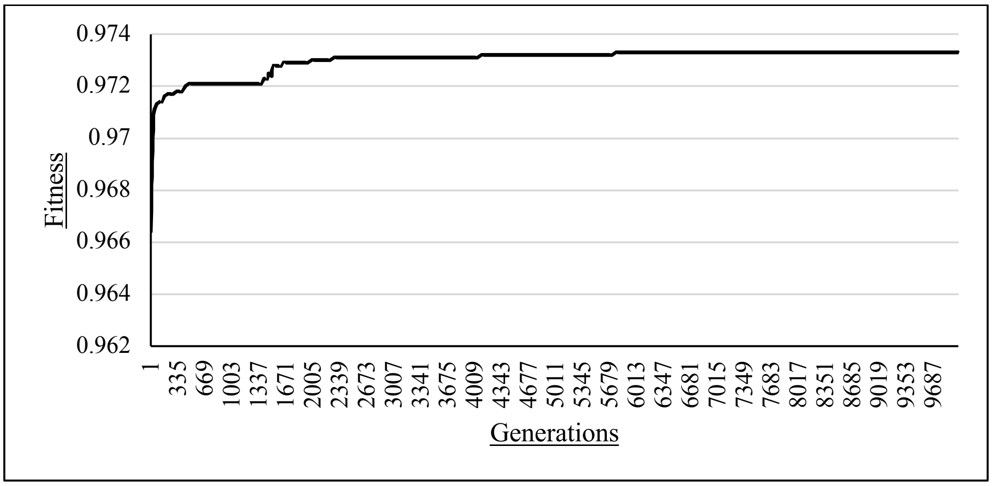

Figure 3: Optimization Process using GA

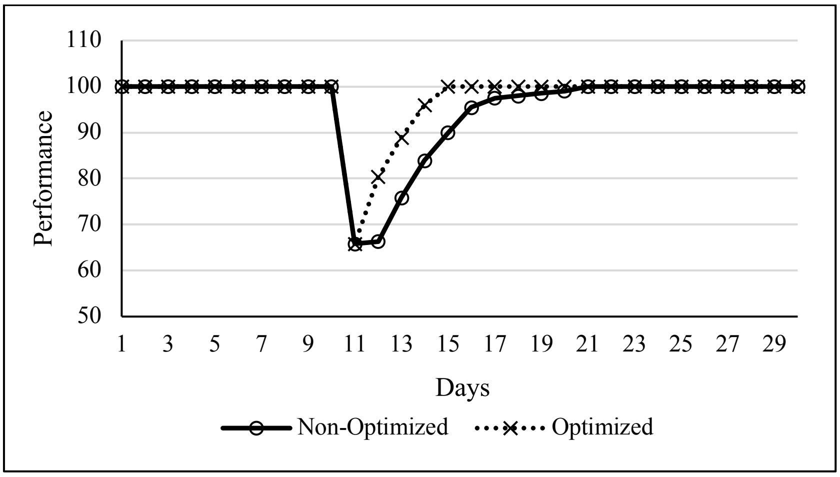

Figure 4: Recovery Curves (Nonoptimized and Optimized)

6.2 Recovery Curves of Each Subsystem

Figure 5 shows the recovery curve of each subsystem under the optimized restoration plan. The horizontal axis represents the simulation time step (day) and the vertical axis, the fitness value of each subsystem. These recovery curves can be used to observe and evaluate the efficiency and effectiveness of the optimized restoration plan. For example, the restoration durations of all subsystems are the same; however, the recovery process for each is slightly different. These differences can be caused by the distribution of agents, location of damaged pipelines, and interdependency within and among subsystems. Therefore, it is necessary to closely examine the effect of these factors to evaluate the optimality of restoration or resilience of the city.

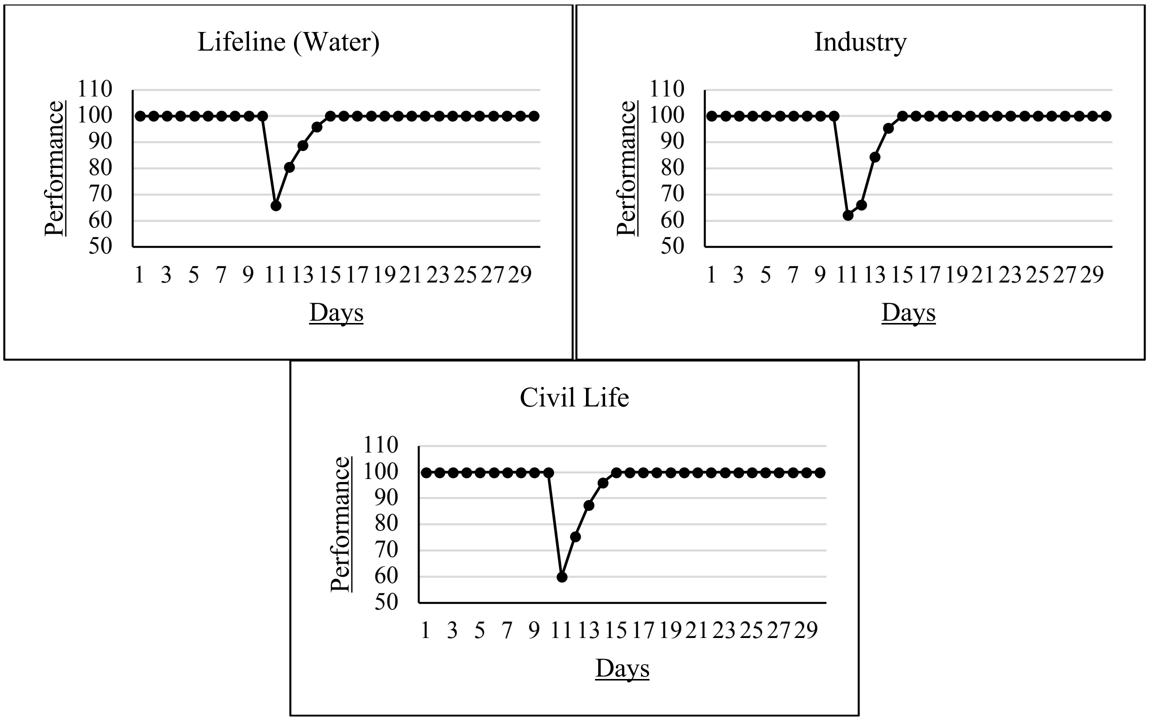

Figure 5: Recovery Curves of Subsystems

6.3 Comparison Among Different Objective Functions

In Figure 5, the area bounded by the recovery curve and y = 100 is called the "resilience triangle," and it is often used as an index for the resilience of the target system [9,10]. Figure 6 shows comparisons of the areas of the resilience triangle as obtained using the optimized restoration plans (1000 generations) under different objective functions defined by the weight coefficients $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, and $\boldsymbol{\gamma}$ in Equation (1). The vertical axis represents the area of the resilience triangle of each subsystem and their sum. In Figure 6, the "Total" value is the sum of the resilience triangles of the three subsystems. In this case, the objective function with $\boldsymbol{\alpha}:\boldsymbol{\beta}:\boldsymbol{\gamma} = \mathbf{1}:\mathbf{1}:\mathbf{1}$ provided the most optimized recovery from the viewpoint of "Total" value. The difference in results arises directly from the different objective functions; however, the objective function that becomes most effective is dependent on the detailed configurations of the city, such as the distribution of population and industry, location and distribution of damage, and multiple interdependencies underlying the city. Therefore, it is important to consider the (1) priority and policy for restoration (objective function), (2) configuration of a city and expected damage, and (3) appropriateness of the effect of the interaction between (1) and (2).

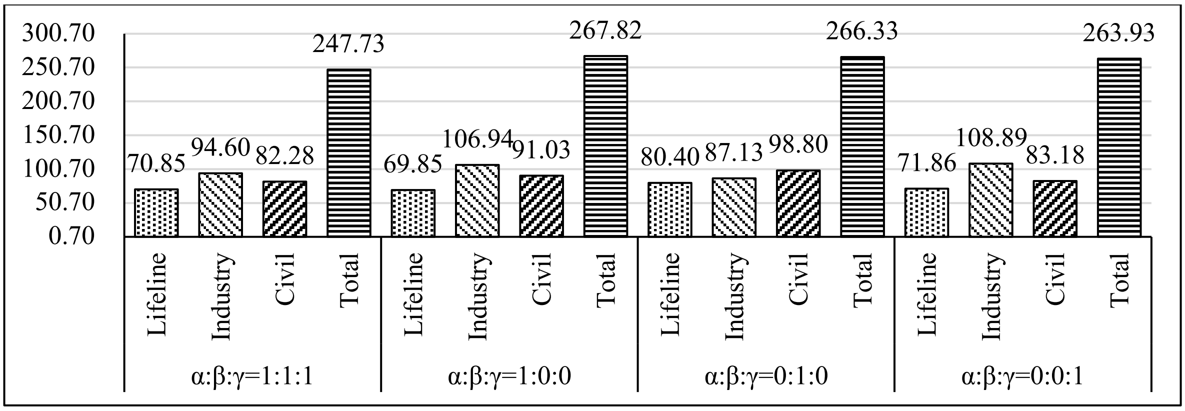

Figure 6: Resilience Triangles (Each Objective Function)

7. CONCLUSION

We are currently developing a high-fidelity water supply system restoration process simulation that incorporates a restoration plan optimization method that uses a GA. By using actual data of a local city in Japan, we constructed a city model for the simulation and conducted test simulations. The simulation results confirm that the GA optimization works appropriately, and the restoration process of each subsystem was observed. The simulation model is not data-dependent; it is possible to create a city model for a different city by using its corresponding data. Therefore, it is easy to expand the target area of the simulation if computational resources are sufficient. From the memory usage in the current simulation, it is estimated that the target area for the simulation can be expanded to the entire city and that the simulation can be conducted on a single workstation.

In our future work, we will improve the lifeline model to consider dynamic changes in water pressure and volume, the details of restoration tasks considering valve operations and required skills and knowledge, and lifeline infrastructures other than water supply and road network. Then, we will conduct simulations under various assumptions and objective functions to provide new insights and knowledge that can lead to better disaster preparedness and management of the target city.

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