Application of Evolutionary Optimization in Structural Engineering

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Abstract. Practical optimization methods including *genetic algorithms* are introduced, based on *evolutionary computing* or *soft computing*. Several application examples are presented to demonstrate and discuss the efficiency and applicability of the described methods.

1 Introduction

Due to the recent advance and development of computer and information technologies, it becomes possible to obtain useful information for decision making with ease. To resolve some problems facing in real life, it is necessary to find out an appropriate solution among possible candidates under several constrained conditions. Therefore, most of these problems are belonging to a kind of optimization problems. However, most of optimization problems being studied are solved under ideal circumstances. Most of real life problems are very large and complicated ones with vague or uncertain objective functions and constrained conditions, different from the ideal circumstances.

Under such circumstances, evolutionary computing has been paid great attention and recognized as a powerful tool for optimization of various practical problems. Evolutionary computing uses iterative procedures, such as growth or development in a population. This population is then selected in a guided random search using parallel processing to achieve the desired end. Such processes are often inspired by biological mechanisms of evolution. Evolutionary computing includes evolutionary programming, genetic algorithm, genetic programming, immune algorithm, learning classifier system, particle swarm optimization, ant colony optimization, etc. Among them, genetic algorithm has been widely used in various fields, because it is a representative method of the evolutionary computing and has a good ability to find out quasi-optimum solutions with ease.

In this paper, several practical optimization methods including GA are introduced, which are based on "evolutionary computing" or "soft computing". Soft computing covers fuzzy decision making, neural networks, and so forth. Several application examples

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are presented to demonstrate and discuss the efficiency and applicability of the methods described here.

2 Structural Vibration Control Using Soft Computing Techniques

In Japan, many high-rise structures have been constructed due to the recent advance of structural material and construction technology. Since the high-rise structures are generally very flexible, vibration control is essential to maintain safety and reliability of the structures. Especially, natural disasters which cause the strong vibration, like typhoon and earthquake should be considered in their design and construction.

Under such situations, a lot of researches on the vibration control have been done in the past [1], most of which do not consider the structural and environmental changes in time. Those systems may lose the performance when the environment has a perceptible change. In actual cases, the characteristics of structures may change due to the structural degradation and the addition of other facilities to the structure. This implies that it is necessary to deal with the structural and environmental changes when designing the vibration control system. There are some robust and adaptive systems that can consider the change of environment. However, in those systems, the structural performance in the static environment may be reduced. In the case, it is essential to adapt to the changing environment quickly while maintaining the performance in the static environment.

In this paper, a new structural vibration control system is described, which can adapt to the change of structural systems and environments, by introducing the learning ability. In this system, it is necessary to prevent the reduction of the performance in the static state, while improving the effectiveness of adaptation and the performance after learning. This system has two different controllers: a robust controller used for the static state and an adaptive controller following the change of environment. By using these two controllers properly, it is possible to achieve a good control performance under any situation. Fuzzy controller is employed for the adaptive controller that can adapt to the change of structural systems, in which the steepest descent method is employed for the learning method. In addition to the two controllers, the system has a judgment ability to recognize the change of environment based on structural response, external force, and control power. Through numerical and model experiments, it is concluded that the system can provide a good control for the unforeseen and incidental changes of external loads and conditions.

2.1 Vibration Control System

The present system has two controllers and one judgment machine. While both controllers calculate control force from structural response and external force all the time, the system uses one of the outputs provided by the two controllers. The structure of the system is shown in Fig. 1.

2.1.1 Robust Controller

In the robust controller, the control force is calculated by fuzzy-neural network system [2, 3]. Although fuzzy-neural network is one of neural networks [4], it can provide the

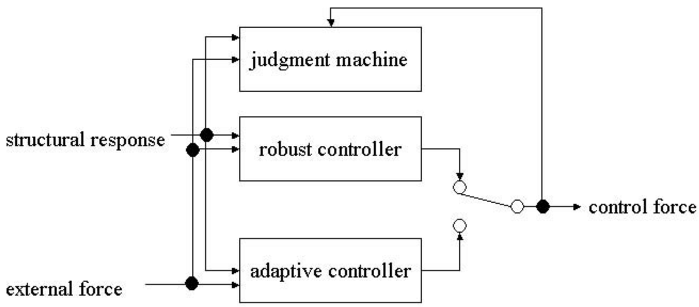


Fig. 1. Structure of the system

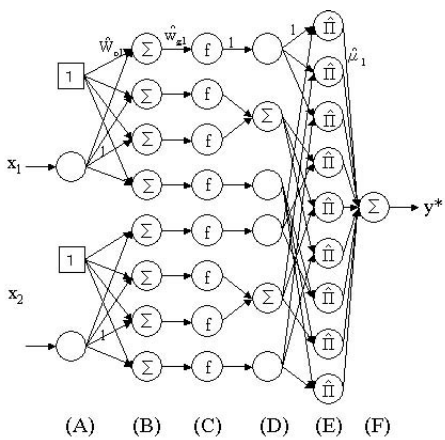


Fig. 2. Structure of fuzzy-neural network

calculating results equal to the fuzzy reasoning method. Therefore, it has characteristics of both neural network and fuzzy reasoning, namely, learning ability of neural network and robustness of fuzzy reasoning. The structure of fuzzy-neural network system is shown in Fig. 2.

This system uses the simplified fuzzy reasoning in which the consequent part is expressed in terms of crisp numbers. In Fig. 2, layers A to D correspond to antecedent parts, and layers E to F correspond to consequent parts. Membership functions are expressed by sigmoid function, and their central values are depicted by the weights between A and B and gradients are depicted by the weights between B and C. Consequent parts are weighted from E to F. Using the sigmoid function, it is possible to define the shape of membership functions in anti-symmetrical forms. Thus, it is possible to realize a better fitting and a better control than with symmetrical membership functions. Those three kinds of weights are learned using the back propagation algorithm.

The robust controller has a learning ability, which is not performed under control, and can avoid over-learning and over-reaction to the change of state. In the system, the neural network has already learned good control patterns by the optimal control theory with the same structure. This means that the neural network may be able to have a control performance equivalent to the optimal control theory. The fuzzy-neural network used here can calculate faster and has robustness, because its structure includes the fuzzy reasoning process. In other words, it can calculate the control force providing good performance equivalent to the optimal control theory in shorter time, and the deterioration of performance at the change of environment is smaller than with the optimal control theory.

2.1.2 Adaptive Controller

For the adaptive controller, the control force is calculated by fuzzy control with a learning mechanism using the steepest decent method. Since the learning method is the same as for the neural network, this fuzzy control system is called neuro-fuzzy system. The neuro-fuzzy system has also the characteristics of both neural network and fuzzy reasoning that are the learning ability of the neural network and the robustness of the fuzzy reasoning. However, neuro-fuzzy structure is simpler than fuzzy-neural network, and therefore the learning is faster and convergence is generally quick. This implies that neuro-fuzzy system is well suited to adaptive controller. In the present system, Gauss function is employed for the membership function. The neuro-fuzzy system can tune the membership functions whose consequent parts are tuned with the steepest decent method by fitting the teaching data. Then, it is necessary to prepare teaching data to learn, however it is impossible to collect the complete teaching data, because the state is so quickly changing that the optimal solution cannot be identified. In other words, if the state of structure is changing, it is not able to know the exact vibration characteristics under the control. In this research, structure response after control is given to the neuro-fuzzy system, in which the system learns the teaching data that are created when the structural response velocity is smaller than that under the previous control. Namely, the teaching data are supposed to be a vector with the inverse direction of structural response. The learning is done at each step. In this way, good rules of reducing the vibration of structure are obtained. Moreover, the calculation is implemented in a faster manner, and the controller has robustness, because the calculation method is based on fuzzy reasoning.

2.1.3 Judgment Machine

Judgment machine is always checking the performance of robust controller to find out the reduction of the performance based on the structural response, external force, and control power. When the vibration characteristics change, some difference appears on those three data. If the structural response differs even for the same external force and the same control power is outputted, judgment machine can recognize some change of environment.

2.1.4 Model Experiment

To validate the performance of each controller, model experiment using rigid frame model is conducted. In the experiment, the structure and environment are not changed. As external force, actual earthquake data observed at Kobe in 1995 are used. The results

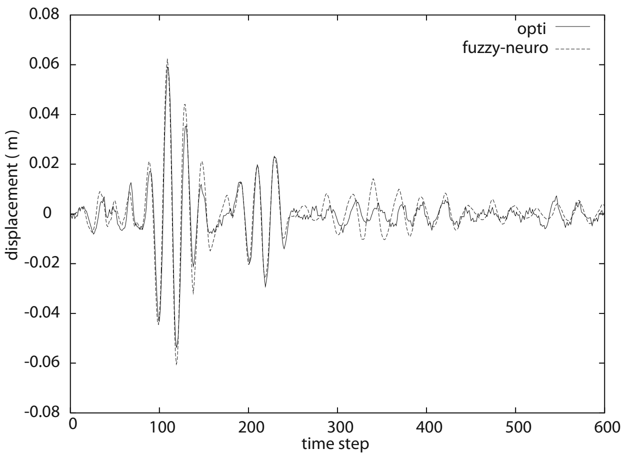


Fig. 3. Experiment result of robust controller

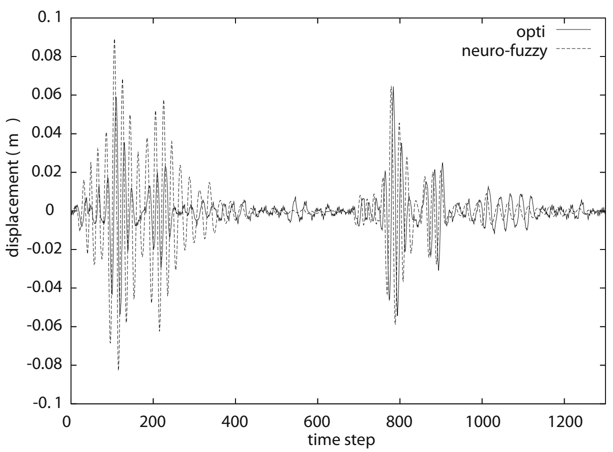


Fig. 4. Experiment result of adaptive controller

of both controllers are shown in Figs. 3 and 4, together with the results of optimal control theory. The robust controller has seven membership functions, which are allocated at even intervals at first. The robust controller has already learned a part of results given by the optimal control theory. However, the input patterns to the system are unknown at the experiment. From Fig. 3, it can be confirmed that the robust controller has as good performance as that by the optimal control theory. In other words, the robust controller can obtain good control rules that are equally efficient as those of the optimal control theory. On the other hand, the adaptive controller has no information regarding the structure and environment at first. The controller has also seven membership functions, in which all consequent parts are initialized to be zero. At the initial stage, the adaptive controller cannot control well and there are big differences from that of the optimal control theory, because it has no information about the environment. However, the performance of control is gradually improved step by step as the learning proceeds. Finally, the performance of adaptive controller becomes equal to the optimal control theory, as shown in Fig. 4. From this result, it is confirmed that this controller can adapt quickly and rightly even though it has no knowledge about the structure and environment. This means that the present system can adapt to the changing environment, therefore it is useful for the control under the dynamic environment.

2.1.5 Numerical Example

To demonstrate the effectiveness of the present system, numerical experiment is done. In this experiment, the frequency characteristic of the structure is changed. The weight of the structure is increased from time to time. In the experiment, the external force is calculated from the actual wind velocity of the 9th typhoon in Osaka on July 26, 1997. This data are observed at the interval of 0.05 second and the total number of data is 30,000. The numerical results by the present system are shown in Fig. 5, comparing with the results by the optimal control theory. In the experiment, the structural weight becomes double after 500 steps. At first, both the systems show almost the same performance at the static state. When the structural characteristics begin to change, some difference appears. While the difference is small at first, the performance of the present system provides better results than the optimal control theory, because of the robustness of the present system. As time proceeds, the difference of performance becomes larger gradually. This shows that the proposed system can adapt to the change of structural characteristic. Since the present system could identify the change of structure and environment, it switched the controller from the robust one to the adaptive one efficiently. The adaptive controller could adapt to the new environment quickly.

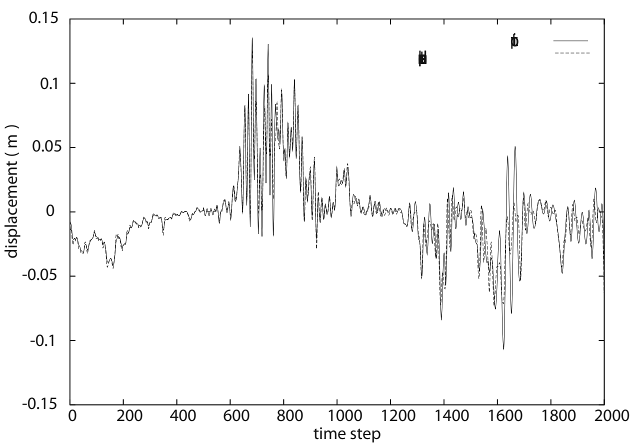


Fig. 5. The numerical results by the present system

3 Aesthetic Design of Bridge Structures

In recent years it is becoming important to consider the aesthetic design factors in the design of bridges. Various researches (e.g. [6]) on the decision-support systems for aesthetic design of a bridge have been made in the past. Here, a practical decision support system for aesthetic design of bridge handrails is introduced. In the design of a bridge handrail, outsourcing the design works to a specialized designer to ensure an aesthetically satisfactory design can cause not only budgetary problems, but also a gap between what the designer imagines and what the engineers think on the structural design.

This paper takes the view that it is possible to obtain new designs by combining components for handrails which were designed in the past, because it would not be easy to create an original new design. Moreover, such use of handrail components designed in the past will be considered to allow candidate aesthetic designs smoothly because there will be no structural problems with components designed in the past.

In this paper, several attempts are presented to develop a decision support system for aesthetic design of bridge handrails. The decision support system consists of the evaluation system using neural network and the optimization system based upon immune algorithm. Thus, it is confirmed that the present system is effective for the aesthetic design of bridge handrails by means of several numerical examples. Furthermore, some of the results obtained are visualized through the use of computer graphics (CGs) and compared.

3.1 Immune Algorithm and Neural Network

Immune algorithms [7] are a kind of optimal solution search algorithms allowing the diversity of solutions to be retained and multiple quasi-optimal solutions to be obtained. It is considered that immune algorithms are suitable for practical aesthetic designing because of these characteristics, which allow two or more different quasi-optimal solutions rather than a single optimal solution to be obtained to a problem which is difficult to evaluate in a standardized manner, such as an aesthetic design. Consequently, an engineer can select an appropriate candidate from them based on his subjective judgment and preferences.

A neural network is a computer simulation of a neuron network. It is considered that characteristics of a neuron network can be utilized to make evaluations of bridge handrails designed by experts to acquire the touch of an expert. Therefore, a near-expert level evaluation can be provided through the use of a neural network without an expert, if once the necessary knowledge is acquired through the learning process.

3.2 Overview of Decision Support System for Aesthetic Design of Bridge Handrails System

The user (decision maker) who wishes to create aesthetic designs of a bridge handrail inputs the following data for the bridge handrail to be designed:

1. The design concepts.
2. The surrounding environment.
3. The configuration of the bridge.
4. The color of the bridge components other than the handrail.

An interactive input system is employed by selecting from items stored in it. Based on the input data two or more quasi-optimal solutions are searched and found using an immune algorithm and a neural network, and candidate aesthetic designs are presented. The flow of the processing by the system is shown in Fig. 6.

One hundred and five photographs of existing bridge handrails are evaluated individually and the results are learned using the neural network. The touch of an expert can be acquired by making evaluation in this manner of bridge handrails that were designed by experts. Therefore, a near-expert level evaluation can be provided through the use of the neural network without an expert once the necessary knowledge is acquired through the learning process.

Then a search for two or more quasi-optimal solutions is made using the neural network that learned the necessary knowledge as an evaluation function for the immune algorithm. As mentioned above, immune algorithms are suitable for aesthetic designing because they allow two or more different quasi-optimal solutions rather than a single optimal solution to be obtained so that the human decision makers can select an appropriate candidate from them based on their subjective judgment and preferences.

3.2.1 Aesthetic Design Items

The surrounding environment, bridge configuration, colors (handrails and except handrails) and handrail components are employed as the aesthetic design items. The photographs of existing bridges are used as the data for the learning with the neural

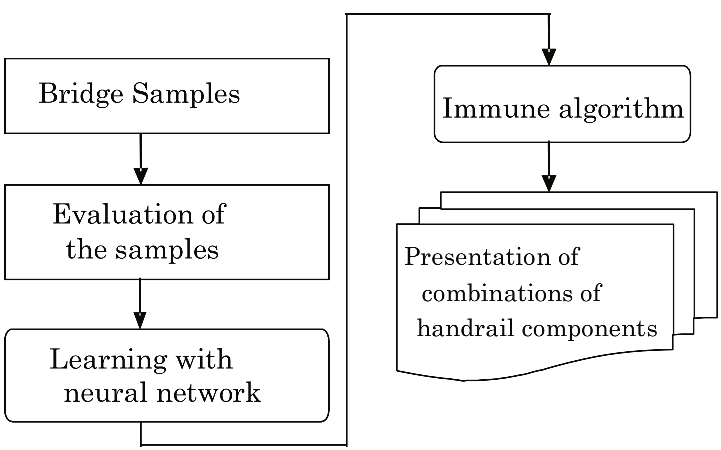


Fig. 6. Flow of the processing by the system

network. Each of these photographs is treated as a sample (i.e. one learning data piece). Explanation of each of aesthetic parameters follows.

3.2.2 Surrounding Environment

The 14 kinds of surrounding environments assumed from the photographs were set up. These are shown in Table 1. In the genetic representation used in this system, 1 or 0 is used to indicate that each of the environmental components is present or not, respectively.

Table 1. Environmental factors

Blue sky	Rice paddies
Cloudy	River
White clouds	Sea
Mountains (green leaves)	Urban area (buildings)
Mountains (brown leaves)	Residences (houses)
Mountains (red leaves)	Snow
Rock or soil	Pavement

3.2.3 Bridge Configuration

The classification of bridge configurations shown in Table 2 is used. The 105 samples are also broken down in Table 2.

Table 2. Bridge configuration classification and sample number

Bridge	Sample Number
Girder bridge	88
Truss bridge	2
Arch bridge	6
Suspension bridge	2
Cable-stayed bridge	5
Rigid frame bridge	2

3.2.4 Color of Bridge Components

As the options for the “color of bridge components”, the 16 colors are considered, which are close to the colors used for the handrails and other bridge components (girders, arch sections, etc.).

Table 3 shows these colors in 3 different color systems (the Mansell value system, the JIS and Japan Paint Manufacturers Association (JPMA) color systems) for ease of use.

Table 3. Color options

JIS	JPMA	Mansell
Red	T07-40X	7.5R4/14
Brown	T15-30F	5YR3/3
Cream	T25-85F	5Y8.5/3
Celadon	T35-70H	5GY7/4
Jasper green	T37-50D	7.5GY5/2
Light greenish blue	T55-50P	5BG5/8
Light blue	T65-80D	5B8/2
Baby blue	T72-70D	2.5PB7/2
Saxon gray	TN-50	N-5
Dayflower	T69-50T	10B5/10
Rose pink	T12-70L	2.5YR7/6
Snow white	TN-95	N-9.5
Yellowish brown	T19-60F	10YR6/3
Sky gray	TN-80	N-8
India ink	TN-10	N-1
Silver		

3.2.5 Handrail Components

In this system, bridge handrails are made up of upper, intermediate and lower bridge handrail components and bridge handrail columns. Each part was classified as shown in Fig. 7.

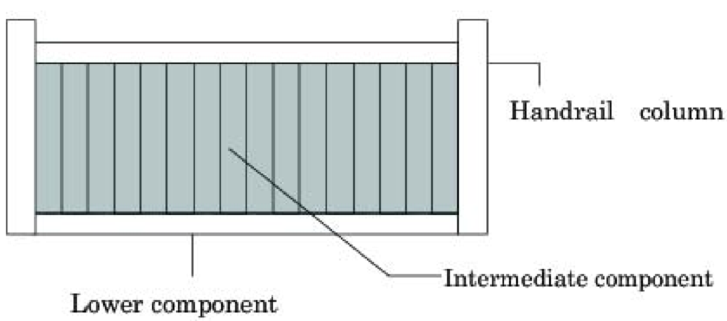


Fig. 7. Handrail components

3.2.6 Design Concepts

To realize the aesthetic design of bridges in this system, several concepts are prepared, which are summarized in Table 4. The user can select the desired design concepts. Two or more concepts can be selected.

Table 4. Design concepts

Symbolic value
Uniqueness
Reliability (Peaceful)
Friendly
Nobleness
Internationality
Harmony with the surrounding environment

3.2.7 Evaluation

105 photographs of the bridges that really exist are used for evaluation. The aesthetic parameters of each sample (photograph) were coupled with the corresponding data that were input into the neural network and were represented as a gene for the immune algorithm. Genes that represent aesthetic parameters in binary figures, i.e., 0 and 1 were used so that genetic codes are represented as one-dimensional bit rows.

1. Surrounding environment: 14 types, 14 bits.
2. Bridge configuration: 6 types, 3 bits.
3. Colors (handrails and bridge components other than handrails): 16 types, 4 bits.
4. Upper handrail components: 4 types, 2 bits.
5. Intermediate handrail components: 64 types, 6 bits.
6. Lower handrail components: 4 types, 2 bits.
7. Handrail columns: 16 types, 4 bits.

As shown in Fig 8, these are represented as 39-bit genes.

The genes shown in Fig 8 represent the following conditions:

1. Surrounding environment: blue sky, white clouds, mountains (green leaves), urban area (buildings), pavement.
2. Bridge configuration: girder bridge.
3. Color of bridge components other than bridge handrails: baby blue.
4. Color of bridge handrails: baby blue.
5. Handrail components: upper components: Type 1; intermediate components: Type 54; lower components: Type 1; handrail columns: Type 2.

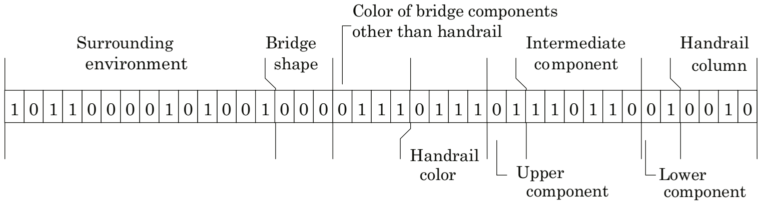


Fig. 8. Gene row of aesthetic parameters

In the application of immune algorithm to a gene, the “surrounding environment”, “bridge configuration” and “color of bridge components other than handrails” parameters are fixed to the values (options) selected by the system user.

Each bridge sample (photograph) is evaluated with respect to the degree to which it matches the design concepts selected out of the seven design concepts shown in Table 4, using an integer scale of zero to ten. The results are used as the training data for the neural network, which are used as the evaluation function for the immune algorithm after it has learned the necessary knowledge. The result of an evaluation of a sample may differ from another evaluation of the same sample made at a different time or on a different day or may become a different one when the order of the examination of the samples (photographs) is changed. Some fluctuations are inevitable because it is humans that make evaluations, but it is possible to make the range of fluctuation narrow by utilizing the knowledge of experts, who are more consistent than non-experts in making technical evaluations. It is also considered that looking through all samples before starting evaluations will help reduce fluctuations.

By having the neural network learn the results of samples evaluations (learning data), it becomes possible to evaluate the data about which learning has not been done. Thus by using the neural network that learned the necessary knowledge as the evaluation function for the immune algorithm, new data can be evaluated to obtain two or more quasi-optimal solutions.

The neural network outputs the evaluation result for the selected design concepts, and the total of the evaluation values for the target design concepts is used as the evaluation value for the candidate of aesthetic design. In the neural computing the following parameters are used:

1. Number of layers of the network: 3
2. Number of patterns learned: 105
3. Number of first layer units: 39
4. Number of second layer units: 46
5. Number of third layer units: 7
6. Number of learning runs (integer value): 1000000
7. Allowable error range (real number value): 0.0000001
8. Learning coefficient (real number value): 0.9
9. Inertia coefficient (real number value): 0.6
10. Gradient of sigmoid function: 1.0

3.2.8 Application Example

The immune algorithm parameters were set as follows:

1. Initial number of antibodies: 20 (gene of the initial antibodies-generation of random number as binary figures 0, 1).
2. Upper limit for the number of memory cells: 5.
3. Number of generations: 300.
4. Manipulation of crossover: uniform crossover, crossover rate: 70.
5. Manipulation of mutation: reversing of a selected bit, mutation rate: 0.3.

6. Thresholds: Tc = 0.8, Tac1 = 0.8, Tac2 = 0.7, Tac3 = 0.8, Tac4 = 0.88.
7. Suppress power: 1.

Examples of actual application of the present system are described as follows.

3.2.9 Design Case 1

1. Surrounding environment: blue sky, white clouds, mountains (green leaves), mountains (brown leaves), rock or soil, river, residence (houses), pavement.
2. Bridge configuration: girder bridge.
3. Color of bridge components other than handrails: cream ((T25-85F)/(5Y8.5/3)).
4. Design concepts: friendly, harmony with the surrounding environment.

Under the above conditions, five design candidates are obtained as shown in Table 5. Table 5 shows that the present system provided five design plans with different characteristics. It is seen that the color selected for the handrail is calm and unremarkable and the configuration of the handrail is simple so that all the plans are satisfactory for such design concepts as "friendly" and "harmony with the surrounding environment".

Table 5. Design candidates for Case 1

	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
Color of handrail	Yellowish brown	Sky gray	Brown	Brown gray	Brown gray
Upper component	Type 2	Type 1	Type 1	Type 1	Type 3
Middle component	Type 7	Type 3	Type 3	Type 1	Type 35
Lower component	Type 2	Type 2	Type 2	Type 2	Type 0
Column	Type 2	Type 0	Type 10	Type 10	Type 10
Friendly	0.8	0.9	0.8	0.9	0.8
Harmony	0.9	0.9	0.9	0.8	0.8

3.2.10 Design Case 2

1. Surrounding environment: blue sky, white clouds, mountains (green leaves), mountains (brown leaves), rock or soil, river, residence, pavement.
2. Bridge configuration: girder bridge.
3. Color of bridge components other than handrails: cream ((T25-85F)/(5Y8.5/3)).
4. Design concepts: unique, harmony with the surrounding environment.

Design Case 2 is the same as Design Case 1 except that the design concept "unique" is used in place of the "friendly". Table 6 presents the design plans obtained by the present system. As shown in Table 6, the configuration of the handrail becomes complicated compared with that of Case 1. The larger the type number of handrail elements is, the more complicated the configuration of handrail becomes. In addition, the color obtained for Plan 3 is red that is not chosen for Case 1. Regarding the design concepts, the second concept of "harmony" is difficult to get high score, when the plan shows the good match to the first concept of "unique", because these two concepts have contradictory characteristics. Thus, this result is considered to be reasonably satisfactory.

Table 6. Design candidates for Case 2

	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
Color of handrail	Saxon gray	Sky gray	Red	Brown	Brown
Upper component	Type 1	Type 1	Type 2	Type 0	Type 2
Middle component	Type 45	Type 47	Type 61	Type 63	Type 37
Lower component	Type 0	Type 2	Type 0	Type 0	Type 0
Column	Type 2	Type 2	Type 2	Type 6	Type 3
Unique	1.0	0.9	1.0	1.0	1.0
Harmony	0.6	0.8	0.7	0.6	0.6

3.2.11 Design Case 3

1. Surrounding environment: blue sky, white clouds, mountains (green leaves), mountains (brown leaves), rock or soil, river, residence (houses), pavement.
2. Bridge configuration: girder bridge.
3. Color of bridge components other than handrails: cream ((T25-85F)/(5Y8.5/3)).
4. Design concepts: internationality, harmony with the surrounding environment.

Design Case 3 has the same design requirements except the design concept: "internationality", whereas "friendly" in Case 1 and "unique" in Case 2. Table 7 presents the design plans obtained for Case 3. By changing the design concept from "friendly" to "internationality", five design plans different from those of Case 1 and Case 2 are obtained. As shown in Table 7, there are more color variations than in Case 1 and the components are different from those used in Case 1, but it is rather debatable whether these candidates of aesthetic designs have internationality. It had been anticipated that intermediate handrail components with European looks would be selected, but in reality relatively simple ones were selected. Also, the colors return to calm ones.

Table 7. Design candidates for Case 3

	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
Color of handrail	Sky gray	Light-greenish blue	Silver	Baby blue	Silver
Upper component	Type 3	Type 3	Type 1	Type 2	Type 0
Middle component	Type 3	Type 19	Type 39	Type 7	Type 1
Lower component	Type 2	Type 0	Type 3	Type 2	Type 2
Column	Type 2	Type 10	Type 10	Type 8	Type 2
Internationality	0.7	0.6	0.8	0.8	0.9
Harmony	0.9	0.8	0.7	0.8	0.6

3.2.12 Design Case 4

1. Surrounding environment: blue sky, white clouds, river, urban area (buildings).
2. Bridge configuration: girder bridge.

3. Color of bridge components other than handrails: cream ((T25-85F)/(5Y8.5/3)).
4. Design concepts: internationality, harmony with the surrounding environment.

Design Case 4 is almost the same as Design Case 3 except for the "surrounding environment", which is changed from the "residence" to "business area". Table 8 presents the candidates of aesthetic design obtained for Case 4. The evaluation values are higher than those given in Case 3 for both "internationality" and "harmony with the surrounding environment". This shows that different results can be obtained only by changing the surrounding environment parameter setting. The handrail components used are little different from those used in Case 3, but the colors are almost the same as those used in Case 3.

Table 8. Design candidates for Case 4

	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
Color of handrail	Baby blue	Silver	Baby blue	Light-greenish blue	Silver
Upper component	Type 0	Type 0	Type 2	Type 0	Type 2
Middle component	Type 21	Type 3	Type 8	Type 1	Type 33
Lower component	Type 1	Type 3	Type 0	Type 2	Type 1
Column	Type 2	Type 8	Type 10	Type 2	Type 10
Internationality	1	1	0.9	1	1
Harmony	0.8	0.9	1	0.9	0.9

3.2.13 Design Case 5

1. Surrounding environment: blue sky, white clouds, mountains (green leaves), mountains (brown leaves), rock or soil, river, residence (houses), pavement.
2. Bridge configuration: girder bridge.
3. Color of bridge components other than handrails: jasper green ((T37-50D)/(7.5GY5/2)).
4. Design concepts: friendly, harmony with the surrounding environment.

This application example is the same as Design Case 1 except that "jasper green" is used in place of the "cream" as the color of bridge components other than the handrails.

Table 9. Design candidates for Case 5

	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5
Color of handrail	Sky gray	Brown gray	Jasper green	Brown gray	Sky gray
Upper component	Type 1	Type 1	Type 3	Type 3	Type 1
Middle component	Type 3	Type 3	Type 38	Type 7	Type 23
Lower component	Type 3	Type 2	Type 2	Type 2	Type 2
Column	Type 2	Type 0	Type 10	Type 0	Type 10
Friendly	0.8	0.9	0.8	0.8	0.8
Harmony	0.9	0.9	0.9	0.8	0.9

The colors obtained are calm and unremarkable, and the configuration of the handrail is rather simple. It can be said that the candidates of aesthetic design provide similar atmospheres to those provided by the candidates of aesthetic design in Case 1 and thus match the design concepts selected.

Fig. 9. Plan 1 of Design Case 1

Fig. 10. Plan 3 of Design Case 1

Fig. 11. Plan 1 of Design Case 2

Fig. 12. Plan 1 of Design Case 3

Fig. 13. Plan 1 of Design Case 4

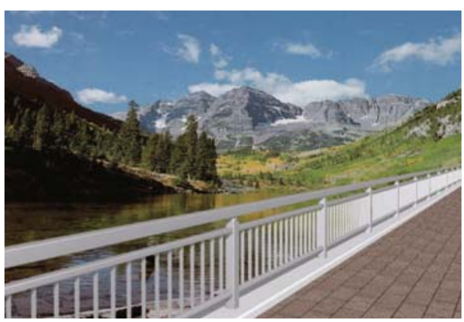


Fig. 14. Plan 1 of Design Case 5

3.2.14 Visualization of Application Example Using Computer Graphics

Some of the candidates of aesthetic design presented by the system in the application example were compared mutually using figures visualized by computer graphics. Plans 1 of Design Cases 1 to 5 and Plan 3 of Design Case 1 were selected to be visualized (a total of 6 plans). To facilitate comparison, the same background was used for all of the plans selected. The visualized candidates of aesthetic design are shown in Figs. 9 to 14.

The plans shown in Figs. 9 and 10 are ones from the same application example (Design Case 1). Although these plans have different features, it is considered that they are ones with similar atmospheres because both of them seem to match the design concepts selected.

The candidate of aesthetic design shown in Fig. 11 is a plan from Case 2, which is the same as Case 1 except that the concept “unique” is used in place of the “friendly”. It is considered that the plan matches the design concept “unique” because the intermediate handrail components have a more complex shape than those of the intermediate handrail components shown in Figs. 9 and 10 and the evaluation value is high.

The plan shown in Fig. 12 is a plan from Case 3, which is the same as Case 1 except that the concept “internationality” is used in place of the “friendly”. This plan may appear to have an international appearance at a first glance in the sense that the handrail color and the shape of the upper handrail components are more uncommon than those used in Figs. 9 and 10, but it is debatable whether this plan has an international appearance because the shape of the intermediate handrail components is rather simple.

The plan (candidate of aesthetic design) shown in Fig. 13 is a plan from Case 4, which is the same as Case 3 except that the surrounding environment is different. It is not possible to compare Fig. 12 with Fig. 13 in terms of the surrounding environment because the same background is used. However, it is considered that this plan matches the design concept “internationality” because the evaluation point is high.

The plan shown in Fig. 14 is a plan from Case 5, which is the same as Case 1 except that “jasper green” is used in place of the “cream” as the color of the bridge components other than the bridge handrails. Although the plans shown in Figs. 9, 10 and 14 have different features, it is considered that they are ones with similar atmospheres because they match the design concepts selected.

4 Optimal Restoration Scheduling for Earthquake Disaster

Japan has been suffering from many natural disasters such as typhoons, tsunami and earthquakes. However, road networks have not been designed to protect against all such natural hazards. Moreover, even the newest design theory cannot guarantee the absolute safety due to the economic constraints. Therefore, it is necessary to develop a synthetic disaster prevention program based on the recognition that road networks may be unavoidably damaged when big earthquakes occur.

In this paper, the early restoration of road networks after the earthquake disasters is focused on. Three issues are dealt with, the first of which is an allocation problem: which groups restore which disaster places, the second is a scheduling problem: what order is the best for the restoration, and the third is an allocation problem: which restoring method is suitable for which disaster places. In order to solve the three problems simultaneously, Genetic Algorithm (GA) is applied, because it has been proven to be very powerful in solving combinatorial problems. In this paper, the relationships among early restoration, minimization of Life-Cycle Cost (LCC), and target safety level of road network are discussed by using Multi-Objective Genetic Algorithm (MOGA). Namely, the following three objective functions are considered:

1. Restoring days are minimized.
2. LCC is minimized.
3. Performance level of road network is maximized.

Then, it is possible to solve the multi-objective optimization problem by making two of the three objective functions as the constrained conditions. For example, the minimization of restoring days is required according to the prescribed performance level and LCC constraints. The predetermination of these requirements may be detrimental. Namely, taking the same restoring days, it may be possible to find solutions that can largely reduce the LCC if the performance level can be slightly decreased. Alternatively, taking the same restoring days, it may be possible to find solutions that can substantially increase the performance level if the LCC is slightly increased.

By introducing the concept of multi-objective optimization into the restoration scheduling for earthquake disasters, it is intended to find several near-optimal restoration scheduling plans. Although single-objective optimization can provide various solutions by changing the constraints, it requires enormous computation time. When selecting a practical restoration schedule, it is desirable to compare feasible optional solutions obtained under various conditions. Thus, a decision support system that can provide several alternative restoration schedules was developed by applying MOGA. Several numerical examples are presented to demonstrate the applicability and efficiency of the present method.

4.1 Road Network Models

Here, it is assumed that a road network is damaged, in which multiple portions are suffered from damage so that it cannot function well. The objective is the realization of quick restoration of the lifeline system. It is intended to determine the optimal allocation of restoring teams and optimal scheduling of restoring process, and optimal allocation of restoring methods. Then, the following conditions should be taken into account:

1. The optimal allocation of restoring teams, optimal scheduling of restoring process, and optimal allocation of restoring methods must be determined simultaneously.
2. A portion of the road network is suffered from several kinds of damage that have a hierarchical relation in time.

As an example of restoration, a road network is considered, which has 164 nodes as shown in Fig. 15. This model corresponds to an area damaged by the 1995 Kobe

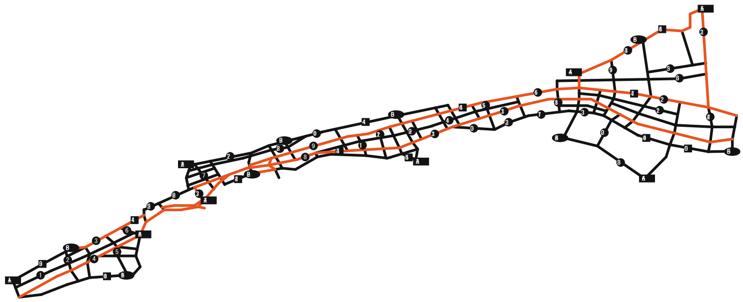


Fig. 15. Road network model

Table 10. Data of work (*A*)

Team of work (*A*)	Ability	Previous works before scheduling
1	15	0
2	30	0
3	12	0
4	17	37
5	18	0
6	23	36
7	25	0
8	35	38

Table 11. Data of work (*B*)

Team of work (*B*)	Ability	Previous works before scheduling
1	15	43
2	20	46
3	25	48
4	10	0
5	17	0
6	30	49
7	23	0
8	27	0

earthquake. For this road network, the following restoration works are necessary to recover the function:

1. Work (*A*): work to clear the interrupted things, 38 sites (1 - 38)
2. Work (*B*) : work to restore the roads, 50 sites (1 - 50)

Table 12. Work (A)'s damage level and rank of importance

Link	Damage level	Rank of importance	Link	Damage level	Rank of importance
1	242	1	20	582	1
2	223	2	21	542	1
3	625	3	22	451	3
4	312	3	23	434	3
5	554	1	24	311	3
6	514	1	25	441	2
7	311	1	26	412	2
8	473	3	27	531	2
9	300	3	28	156	2
10	321	3	29	556	1
11	656	1	30	520	2
12	380	1	31	551	3
13	501	3	32	166	1
14	302	1	33	513	1
15	312	3	34	531	3
16	321	3	35	495	1
17	231	1	36	424	1
18	534	2	37	337	3
19	171	1	38	564	2

Then, the limitations and restrictions of each work should be considered, for instance, work (B) should be done after work (A). Work (B) consists of the following three works: work to repair the roads, work to reinforce the roads and work to rebuild the roads. The waiting places of restoring teams for work (A) and work (B) are shown by the numbers A (1-8) and B (1-8), respectively. Tables 10 and 11 show the ability to restore and the previous works before scheduling of each team. Tables 12 and 13 show the damage level and the rank of importance.

4.2 Restoration Scheduling

Weighting factors are prescribed for the links with damage, which are denoted by W_i $(i = 1, \ldots, n_L)$. n_L is the total number of damaged links. Then, the restoring rate after q days, $R^{(q)}$, is expressed as follows:

$$R^{(q)} = \frac{\sum_{i \in J^{(q)}} W_i \times l_i}{\sum_{i \in J^{(0)}} W_i \times l_i} \tag{1}$$

where l_i is the distance of the i-th link, $J^{(0)}$ is the set of damaged links, $J^{(q)}$ is the set of restored links until q days after the disaster, and W_i is the weighting factor of the

Table 13. Work (B)'s damage level and rank of importance

Link	Damage level	Rank of importance	Link	Damage level	Rank of importance
1	153	1	26	146	2
2	453	2	27	366	2
3	496	3	28	311	2
4	464	3	29	145	1
5	133	1	30	425	2
6	415	1	31	413	3
7	355	1	32	231	1
8	531	3	33	245	1
9	246	3	34	353	3
10	623	3	35	461	1
11	445	1	36	131	1
12	154	1	37	455	3
13	613	3	38	564	2
14	444	1	39	631	1
15	366	3	40	322	2
16	615	3	41	464	3
17	641	1	42	114	1
18	151	2	43	415	1
19	254	1	44	700	1
20	654	1	45	311	3
21	561	1	46	211	3
22	125	3	47	344	3
23	345	3	48	407	3
24	462	3	49	512	2
25	456	2	50	423	2

i-th link. Then, the objective function can be calculated by using the restoring days and the restoring rate. The relation between restoring days and restoring rate is shown in Fig. 16. The area of the uncolored portion should be minimized to obtain the optimal solution, because this enables not only to shorten the restoring days but also to restore the important links faster.

Restoring days are calculated for each restoring work, and the minimum days necessary for each work is given as

$$d = \frac{h}{t_1} \tag{2}$$

where h is the restoration time required to complete the restoration work.

In this paper, the restoration time is calculated by using the restoration rate for each work and the capability value. The relation between the restoration rate for each work and the capability of the teams are shown in Fig. 17. The restoration rate is given as follows:

a) Small damage: In the small damage, there is no difference in capability of each team. The restoration will be completed during a fixed time. Here, 4 hours are assumed.

$$h = h_t \tag{3}$$

b) Moderate damage: In the moderate damage, there are some differences in capability between teams. However, every team can restore the damage.

$$h = \frac{D}{A} \tag{4}$$

where D is the amount of damage and A is the capability of the team, that is, the restoring amount per hour.

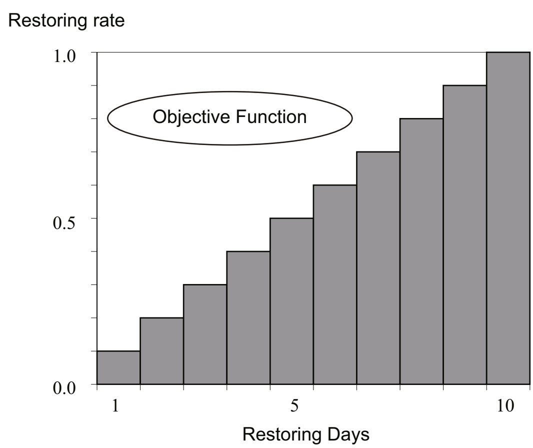
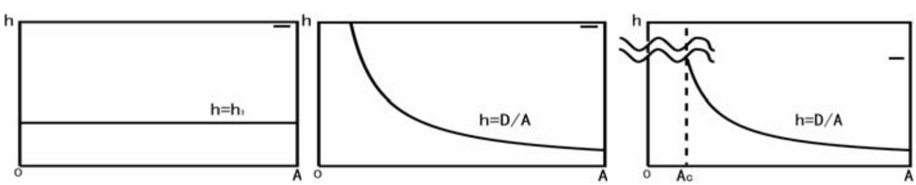


Fig. 16. Objective function



a) Small damage b) Moderate damage c) Large damage

Fig. 17. Relations between restoration rate for each work and capability of teams

c) Large damage: In the large damage, only some teams can restore, because other teams have no restoring equipment and facility necessary for the large damage.

$$h = \begin{cases} \infty, & \text{if } A < A_c, \\ D/A, & \text{if } A \geq A_c. \end{cases} \tag{5}$$

where A_c is the minimum capability which the team can work.

The working hours per day of a restoration team are calculated by Equation (6), where t_m is the moving time to a site given by Equation (7). The shortest distance from the waiting place of the restoration team to the site is considered as L (km), and the moving speed of the team is set to be v (km/h). h_c is the preparation time that is necessary for every work.

$$t_1 = t_0 - 2t_m - h_c \tag{6}$$

$$t_m = \frac{L}{v} \tag{7}$$

4.3 Optimal Restoration Scheduling for Earthquake Disaster Using Life-Cycle Cost

Road networks have not been designed to sustain all natural hazards. Moreover, even the newest design theory cannot guarantee the absolute safety due to the economic constraints. Therefore, it is necessary to develop a synthetic disaster prevention program based on the recognition that road networks may be unavoidably damaged when big earthquakes occur. The purpose of this research is the early restoration of road networks after the earthquake disasters. Three issues are focused on, the first of which is an allocation problem: which groups restore which disaster places, the second is a scheduling problem: what order is the best for the restoration, and the third is an allocation problem: which restoring method is suitable for which disaster places. In order to solve the three problems simultaneously, Genetic Algorithm (GA) is applied. In this paper, an attempt is made to discuss the relationships among early restoration, minimization of LCC, and target safety level of road network by using Multi-Objective Genetic Algorithm (MOGA). Namely, the following three objective functions are considered:

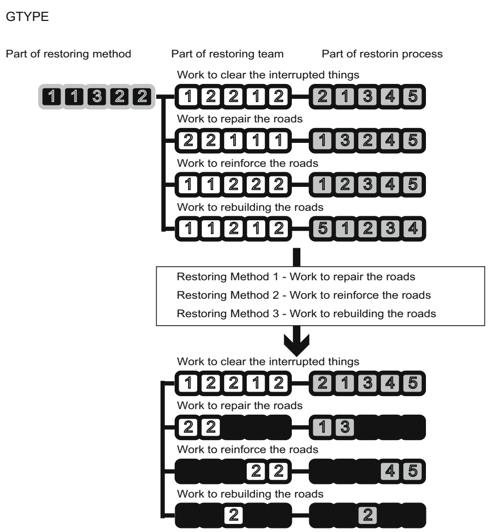
1. Restoring days are minimized.
2. LCC is minimized.
3. Target safety level of road network is maximized.

Then, it is possible to solve the multi-objective optimization problem by making two of the three objective functions as the constrained conditions. For example, the minimization of restoring days is required according to the prescribed target safety level and LCC constraints. The predetermination of these requirements may be detrimental. Namely, taking the same restoring days, it may be possible to find solutions that can largely reduce the LCC if the safety level can be slightly decreased. Alternatively, taking the same restoring days, it may be possible to find solutions that can substantially increase the safety level if the LCC is slightly increased.

By introducing the concept of multi-objective optimization into the restoration scheduling for earthquake disasters, it is intended to find several near-optimal restoration schedules. Although single-objective optimization can provide various solutions by changing the constraints, it requires enormous computation time. When selecting a practical restoration schedule, it is desirable to compare feasible optional solutions obtained under various conditions. Thus, an attempt is made in this study to develop a decision support system that can provide several alternative restoration schedules by applying MOGA.

4.4 Objective Functions

In this study, restoring days, LCC and safety level are used as objective functions. Restoring days are minimized, LCC is minimized, and safety level is maximized. There are trade-off relations among the three objective functions. For example, safety level decreases when LCC decreases, and safety level is extended due to the extension of restoring days. Then, multi-objective optimization can provide a set of Pareto solutions that cannot improve an objective function without making other objective functions worse. In this study, DNA structure is constituted as shown in Fig. 18, in which DNA of each individual consists of three parts such as restoring method, allocation of restoring teams, and schedule of restoring process. Using the coding, it is possible to determine the optimal allocation of restoring teams, optimal scheduling of restoring process, and optimal allocation of restoring methods simultaneously.



PTYPE

	Team	restoring process 1st	restoring process 2nd
Work to Clear the interrupted things	1	2	4
	2	3	5
Work to repair the roads	2	1	3
Work to reinforce the roads	2	4	5
Work to rebuilding the roads	2	2	

Fig. 18. DNA structure

Then, the three objective functions are expressed as follows.

4.4.1 Restoring Days

The relation between restoring days and restoring rate is shown in Fig. 16. The area of the uncolored portion should be minimized to obtain the optimal solution, because this enables not only to shorten the restoring days but also to restore the important links faster.

4.4.2 Life-Cycle Cost

Life-Cycle Cost (*LCC*) is defined as the total maintenance cost in terms of road network and all the entire bridges during their lives. In this paper, restoring method is defined by three kinds of methods: work to repair the roads, work to reinforce the roads, and work to rebuild the roads. Then, restoring cost of each work is defined by

$$RC = C_b \times D_{degree} \tag{8}$$

where C_b is the basic restoring cost and D_{degree} is the level of damage defined in Table 14. Table 15 presents the basic costs and safety levels by the restoring methods. Fig. 19 shows the performance levels of restoring methods. Maintenance cost of each work after restoring is defined by

$$MC = M_b \times D_r \tag{9}$$

where M_b is the basic maintenance cost presented in Table 15 and D_r is the level of deterioration defined in Table 14. Here, the accumulated maintenance cost is considered for 50 years.

Then, the objective function is defined by

$$LCC = \sum_{i \in J^{(0)}} (RC_i + MC_i) \tag{10}$$

where RC_i is the restoring cost of the i-th link, MC_i is the maintenance cost of the i-th link, and $J^{(0)}$ is the set of damaged links.

4.4.3 Safety Level

Safety level depends on the traffic volume and the condition of links. In this research, safety level (*SL*) of the road network is maximized, which is defined by

$$SL = \sum_{i \in J^{(0)}} (I_i + SL_i) \tag{11}$$

where I_i is the importance of the i-th link, S_i is the safety level of the i-th link, and $J^{(0)}$ is the set of damaged links.

Table 14. Levels of damage and levels of deterioration

Link	Work (*A*)	Work (*B*)	Level of deterioration	Link	Work (*A*)	Work (*B*)	Level of deterioration
1	1.70	0.47	0.8	26	1.36	0.45	1.2
2	0.73	0.96	1.0	27	1.33	1.12	1.2
3	1.91	1.61	1.5	28	0.95	1.87	1.2
4	0.94	1.42	1.5	29	1.33	0.44	0.8
5	1.96	0.41	1.0	30	1.26	1.30	1.0
6	1.53	1.27	0.8	31	1.65	1.26	1.5
7	0.63	1.09	0.8	32	0.50	0.71	1.0
8	1.38	1.62	1.5	33	1.54	0.75	0.8
9	1.97	0.75	1.5	34	1.59	1.08	1.5
10	1.02	1.91	1.5	35	0.74	1.10	1.0
11	2.00	1.36	1.0	36	1.27	0.40	1.0
12	1.27	0.47	1.0	37	1.01	0.78	1.5
13	1.56	1.87	1.5	38	1.69	1.72	1.8
14	0.94	1.36	1.0	39		1.93	0.8
15	0.97	1.12	1.2	40		0.98	1.9
16	0.71	1.88	1.2	41		1.42	1.5
17	0.74	1.96	1.0	42		0.35	0.8
18	2.00	0.46	1.0	43		1.27	0.8
19	1.87	0.78	0.8	44		2.14	0.8
20	0.94	2.00	0.8	45		1.56	1.8
21	0.67	1.72	0.8	46		0.65	1.5
22	1.56	0.38	1.2	47		1.05	1.5
23	0.49	1.06	1.2	48		1.24	1.5
24	1.67	0.65	1.5	49		1.57	1.0
25	1.63	1.64	1.0	50		1.29	1.0

Work (*A*): The level of damage for work to clear the interrupted things
Work (*B*): The level of damage for work to restoring the roads

Table 15. The basic costs and safety levels by the restoring methods

Restoring method	Basic restoring cost	Basic maintenance cost	Safety level
Repair	700	3500	0.6
Reinforcement	1200	2000	0.8
Rebuilding	5000	1500	0.9

Basic restoring cost (Ten thousand yen)
Basic maintenance cost (Ten thousand yen)

4.5 Multi-objective Optimization

A multi-objective optimization problem has two or more objective functions that cannot be integrated into a single objective function. In general, the objective functions cannot be simultaneously minimized (or maximized). It is the essence of the problem that trade-off relations exist among the objective functions. The concept of "Pareto optimum" becomes important in order to balance the trade-off relations. The Pareto

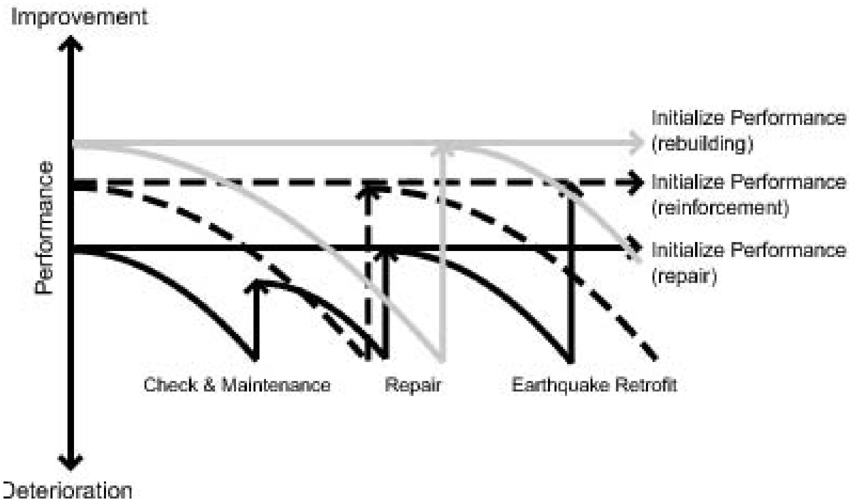


Fig. 19. The performance levels of restoring methods

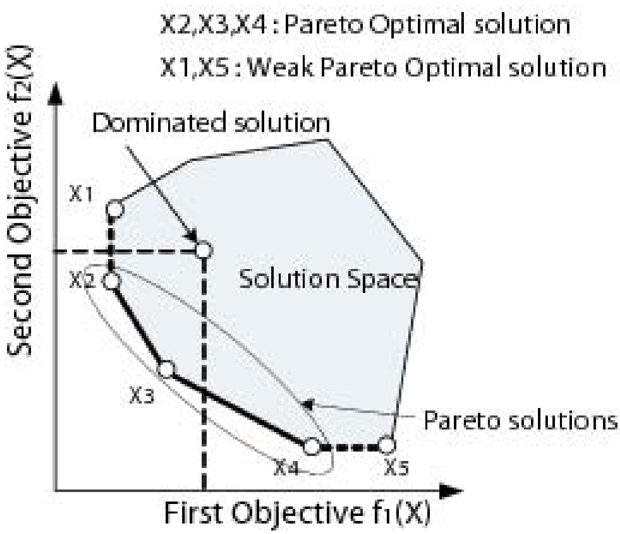


Fig. 20. Cost-effective domain including Pareto solutions

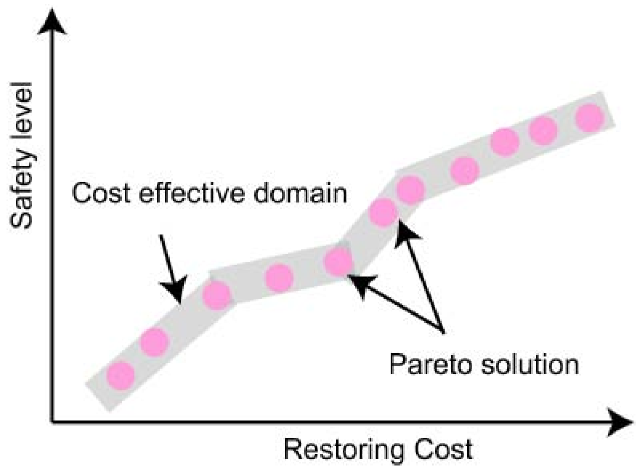


Fig. 21. Pareto solutions in objective space

optimum solution is a solution that cannot improve an objective function without sacrificing other functions (Figs. 20 and 21). A dominated, also called non-dominant, solution is indicated in Fig. 20. GA is an evolutionary computing technique, in which candidates of solutions are mapped into GA space by encoding. The following steps are used to obtain the optimal solutions: a) initialization, b) crossover, c) mutation, d) natural selection, and e) reproduction. Individuals, which are solution candidates, are initially generated at random. Then, steps b, c, d, and e are repeatedly implemented until the termination condition is fulfilled. Each individual has a fitness value to the environment. The environment corresponds to the problem space and the fitness value corresponds to the evaluation value of objective function. Each individual has two aspects: Gene Type (GTYPE) expressing the chromosome or DNA and Phenomenon Type (PTYPE) expressing the solution. GA operations are applied to GTYPE and generate new children from parents (individuals) by effective searches in the problem space, and extend the search space by mutation to enhance the possibility of individuals other than the neighbor of the solution.

GA operations that generate useful children from their parents are performed by crossover operations of chromosomes or genes (GTYPE) without using special knowledge and intelligence. This characteristic is considered as one of the reasons of the successful applications of GA.

4.6 Application of MOGA to Restoration Scheduling

Table 16 presents the parameters of MOGA used here. Fig. 22 present the results obtained by MOGA. Table 17 shows the evaluation values of each solution. Then, the efficiency of MOGA is expressed as follows; for example, comparing solution C with

Table 16. Parameters of MOGA

Population	Probability of crossover	Probability of mutation	Generation
1000	0.6	0.005	1000

Table 17. Evaluation values of each solution

Solution	Restoring days	LCC	Safety level
A	14.234	241343	61.224
B	15.069	242300	62.123
C	16.309	254316	63.496
D	17.421	260416	63.756
E	17.565	265017	74.116
F	17.576	264866	80.011
G	17.546	284954	80.023
H	17.779	289676	80.229
I	17.898	292191	82.054
J	18.325	291942	82.234
K	18.649	301471	82.268
L	18.623	303837	82.302

solution D in safety level, there is no significant difference between the two solutions. However, in restoring days and LCC, solution D is worse than solution C. On the other hand, comparing solution E with solution F, there is no significant difference in restoring days between the two solutions. However, solution F is better than solution E in LCC. Moreover, in safety level, solution F is substantially better than solution E. In Table 17, comparing solution E with solution G, there is no significant difference in restoring days between the two solutions. However, in safety level and LCC, there are significant differences between the two solutions.

In Fig. 23, the vertical axis represents LCC, whereas the horizontal axis represents restoring days. Fig. 24 presents the relation between restoring days and safety level. In Figs. 23 and 24, since restoring days and the other two objective functions have a rather perfect positive linear correlation, it can be said that the other two can have a positive effect if restoring days can be increased. Fig. 25 presents the relation between LCC and safety level. In Figs. 24 and 25, it should be noted that it can be said that the other two objective function can have a positive effect when there is no significant difference in safety level.

Figs. 26 to 29 show the detailed restoration schedule associated with the solution K shown in Fig. 22. In Figs. 26 to 29, compared to the number of work to repair the roads,

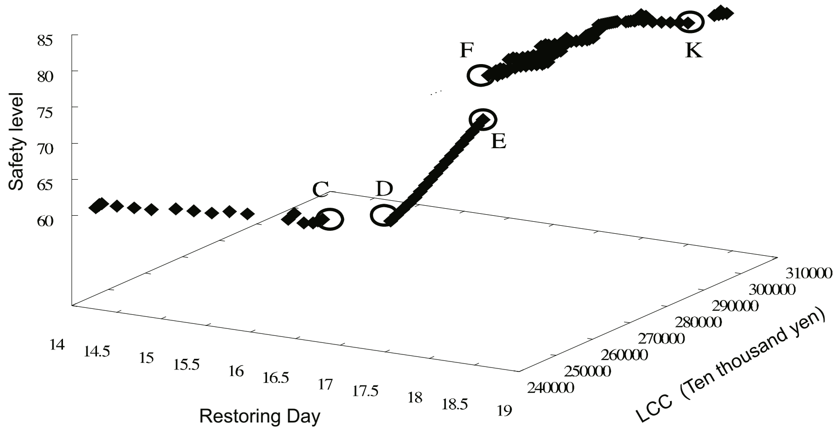


Fig. 22. Pareto solutions obtained by MOGA

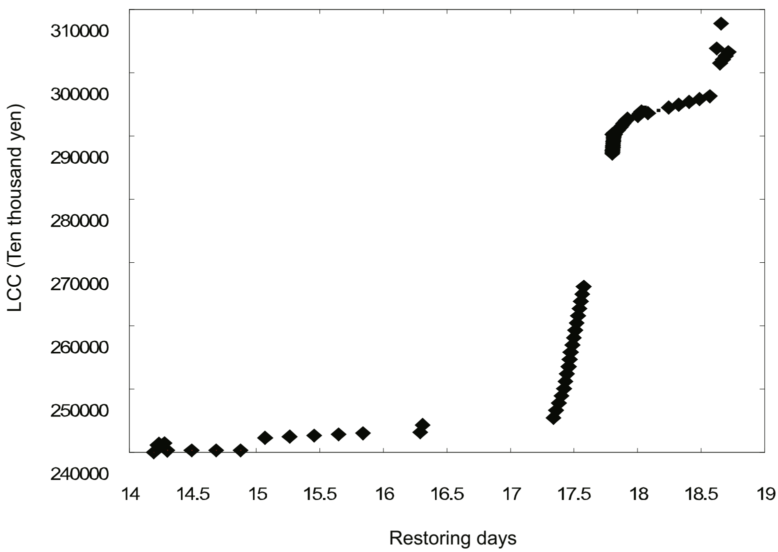


Fig. 23. Relation between restoring days and LCC

there are many works to reinforce the roads and to rebuild the roads, which can increase safety level, in some important links. As will be appreciated from Table 17, comparing solution K with the other solutions, solution K is worse than the other solutions in restoring days. However, solution K is better than the other solutions in safety level.

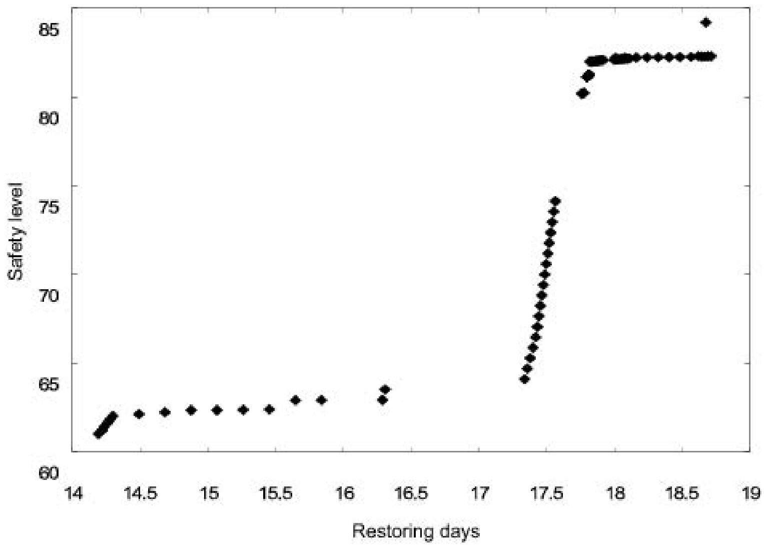


Fig. 24. Relation between restoring days and safety level

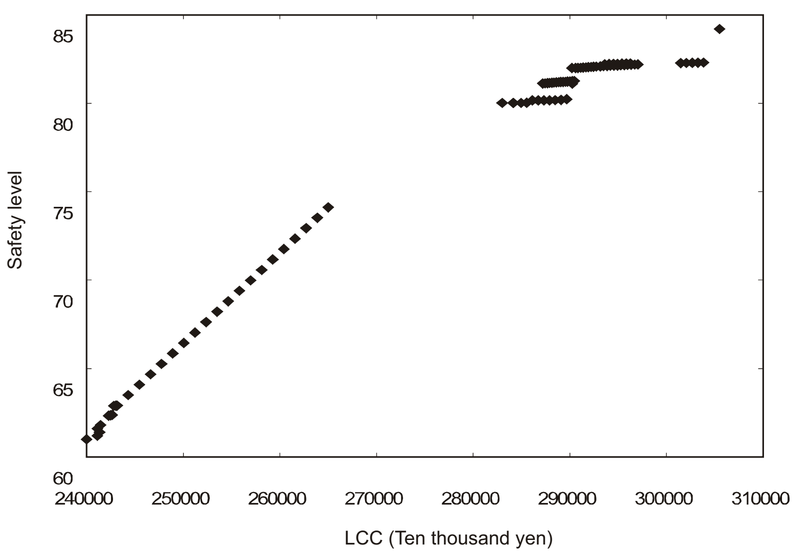


Fig. 25. Relation between LCC and safety level

<table>
<tr><th>Days</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th></tr>
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<tr><td>7</td><td colspan="2">16</td><td colspan="2">2</td><td colspan="4">18</td><td colspan="2">4</td><td colspan="4">3</td><td colspan="2"></td></tr>
<tr><td>8</td><td colspan="2">36</td><td colspan="2">26</td><td colspan="2">31</td><td>1</td><td colspan="2">11</td><td>35</td><td colspan="2">12</td><td colspan="4"></td></tr>
</table>

Fig. 26. Schedule of work to clear the interrupted things

<table>
<tr><th>Days</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th></tr>
<tr><td>Group1</td><td colspan="4">43</td><td colspan="3">32</td><td colspan="6"></td></tr>
<tr><td>2</td><td colspan="3">47</td><td colspan="10"></td></tr>
<tr><td>3</td><td colspan="3">49</td><td colspan="3"></td><td colspan="4">13</td><td colspan="3"></td></tr>
<tr><td>4</td><td colspan="4"></td><td colspan="3">2</td><td colspan="6"></td></tr>
<tr><td>5</td><td colspan="2"></td><td colspan="2">37</td><td colspan="7"></td><td colspan="2">29</td></tr>
<tr><td>6</td><td colspan="2">50</td><td colspan="11"></td></tr>
<tr><td>7</td><td colspan="3">39</td><td colspan="4"></td><td colspan="2">7</td><td>1</td><td colspan="3"></td></tr>
<tr><td>8</td><td colspan="4"></td><td>26</td><td colspan="3">38</td><td colspan="5"></td></tr>
</table>

Fig. 27. Schedule of work to repair the roads

<table>
<tr><th>Days</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th></tr>
<tr><td>Group1</td><td colspan="4">42</td><td colspan="2"></td><td colspan="4">31</td><td colspan="10"></td></tr>
<tr><td>2</td><td colspan="5">45</td><td colspan="2"></td><td colspan="3">23</td><td colspan="5">17</td><td colspan="5">3</td></tr>
<tr><td>3</td><td colspan="3"></td><td colspan="7">25</td><td colspan="3">35</td><td colspan="4">6</td><td colspan="3"></td></tr>
<tr><td>4</td><td colspan="6"></td><td colspan="4">19</td><td colspan="4">4</td><td colspan="6"></td></tr>
<tr><td>5</td><td colspan="5"></td><td colspan="5">28</td><td colspan="3"></td><td colspan="3">22</td><td colspan="4">30</td></tr>
<tr><td>6</td><td colspan="3"></td><td colspan="2">33</td><td colspan="4"></td><td colspan="4">24</td><td colspan="2"></td><td colspan="5">14</td></tr>
<tr><td>7</td><td colspan="15"></td><td colspan="5">9</td></tr>
<tr><td>8</td><td colspan="4">41</td><td colspan="4"></td><td colspan="5">10</td><td colspan="2"></td><td colspan="5">8</td></tr>
</table>

Fig. 28. Schedule of work to reinforce the roads

<table>
<tr><th>Days</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th></tr>
<tr><td>Group1</td><td colspan="10">46</td><td colspan="2"></td><td colspan="12">12</td><td colspan="3"></td></tr>
<tr><td>2</td><td colspan="2"></td><td colspan="11">16</td><td colspan="14">34</td></tr>
<tr><td>3</td><td colspan="4"></td><td colspan="11">15</td><td colspan="11">11</td><td></td></tr>
<tr><td>4</td><td colspan="10">40</td><td colspan="12">18</td><td colspan="5"></td></tr>
<tr><td>5</td><td colspan="11">48</td><td colspan="10">21</td><td colspan="6"></td></tr>
<tr><td>6</td><td colspan="11"></td><td colspan="13">27</td><td colspan="3"></td></tr>
<tr><td>7</td><td colspan="10">44</td><td colspan="11">20</td><td colspan="6"></td></tr>
<tr><td>8</td><td colspan="2"></td><td colspan="13">36</td><td colspan="12">5</td></tr>
</table>

Fig. 29. Schedule of work to rebuild the roads

From the above results, it is confirmed that various kinds of solutions can be obtained by the proposed method. Namely, when selecting a practical restoration schedule, the proposed method enables to compare feasible optional solutions obtained under various conditions.

5 Optimal Maintenance Planning of Bridge Structures Using MOGA

It has been widely recognized that maintenance work is important, because the number of existing bridges requiring repair or replacement increases in the future. In order to establish a rational maintenance program, it is necessary to develop a cost-effective decision-support system that can provide us with a practical and economical plan. Although low-cost maintenance plans are desirable for bridge owner, it is necessary to consider various constraints when choosing an appropriate actual maintenance program. For example, the minimization of maintenance cost requires to prescribe the target safety level and the expected service life time. The predetermination of requirements may loose the variety of possible maintenance plans. Namely, it may be possible to find out a better solution that can largely extend the service life if the safety level can be sensitively decreased even with the same maintenance cost.

It is desirable to discover many alternative maintenance plans with different characteristics. Although a single-objective optimization can provide various solutions by changing the constraints, it requires enormous computation time. When selecting a practical maintenance plan, it is useful to compare feasible solutions obtained under the various conditions. This process is inevitable and effective for the accountability by the disclosure of information. Then, an attempt was made to develop a decision support system for the bridge maintenance that can provide us with several alternative plans by applying Multi-Objective Genetic Algorithm (MOGA). However, it is not easy for the decision maker to choose an appropriate solution from many Pareto solutions. In order to help the decision maker, a 3D graphical system was developed using JAVA techniques. It is important to find out the appropriate repair methods and the branching points of cost effectiveness. Several numerical examples are presented to demonstrate the applicability and efficiency of the present system.

5.1 Concrete Bridge Model

A group of ten concrete highway bridges are considered. The locations of all these bridges along the coast of Japan are indicated in Fig. 30. Maintenance management planning for ten consecutive piers and floor slabs (composite structure of steel girders and reinforced concrete (RC) slabs) is considered. Each bridge has the same structure and is composed of six main structural components: upper part of pier, lower part of pier, shoe, girder, bearing section of floor slab, and central section of floor slab (Fig. 31). In this study, an attempt was made to develop a new searching method for optimization problem. Environmental conditions can significantly affect the degree of deterioration of the structures and may vary from location to location according to geographical characteristics such as wind direction, amount of splash, etc. To take the environmental conditions into account, the deterioration type and year from completion of each bridge are summarized in Table 18.

Table 18. Years from completion and type of deterioration caused by environmental conditions

Bridge number	Years from completion	Deterioration type
B01	2	neutralization of concrete
B02	2	neutralization of concrete
B03	0	chloride attack (slight)
B04	0	chloride attack (medium)
B05	0	chloride attack (severe)
B06	0	chloride attack (medium)
B07	0	chloride attack (severe)
B08	1	chloride attack (medium)
B09	1	chloride attack (slight)
B10	1	chloride attack (slight)

Environmental corrosion due to neutralization of concrete, chloride attack, frost damage, chemical corrosion, or alkali-aggregate reaction are considered as major deteriorations. The structural performance of each bridge component i is evaluated by the associated safety level (also called durability level) P_i which is defined as the ratio of current

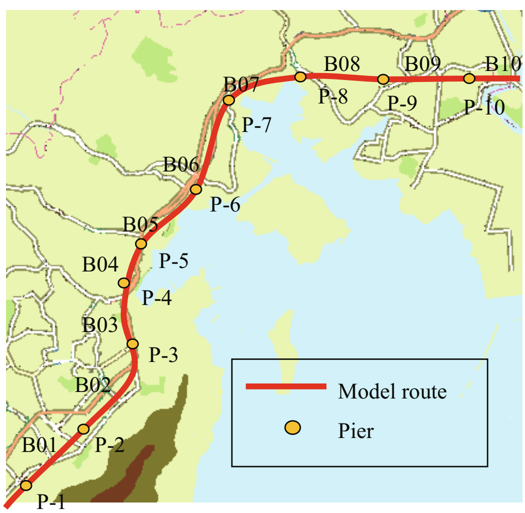

Fig. 30. Location of ten bridges in Japan

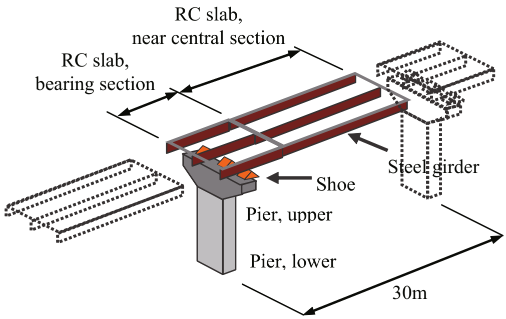

Fig. 31. Main components of a bridge

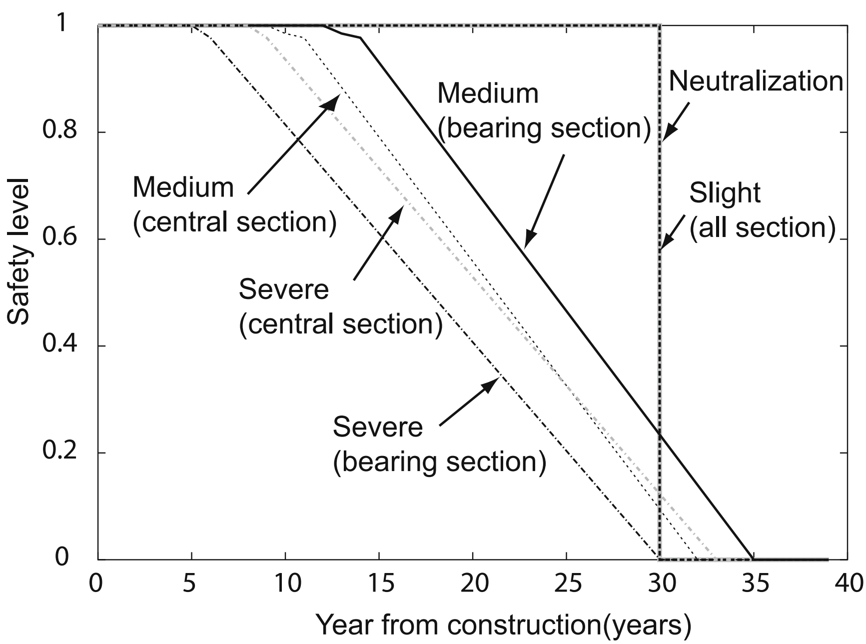

Fig. 32. Typical performance of RC slabs

safety level to initial safety level. Deterioration of a bridge due to corrosion depends on the concrete cover of its components and environmental conditions, among other factors. For each component, the major degradation mechanism and its rate of deterioration are assumed corresponding to associated environmental conditions. Figs. 32, 33,

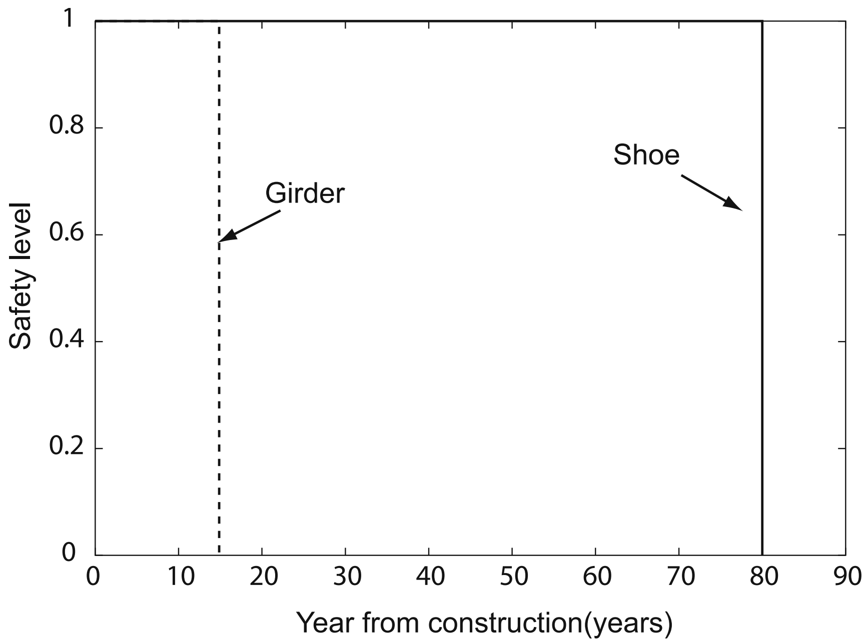

Fig. 33. Typical performance of shoes and girders

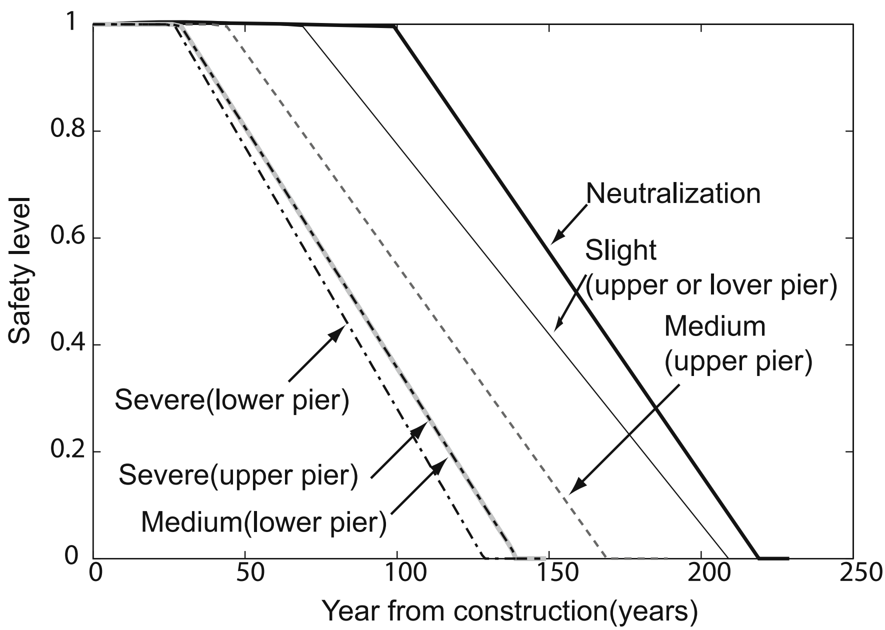

Fig. 34. Typical performance of piers

and 34 show the decreasing patterns of safety levels for RC slabs, shoes and girders, and piers, respectively. Average values are employed here as representative values for each level of chloride attack because the deteriorating rates can vary even in the same environment. The decrease of RC slab performance is assumed to depend on corrosion. Hence, the safety level depends on the remaining cross-section of reinforcement bars. For shoe and girder, the major deterioration mechanism is considered to be fatigue due to repeated loadings. The decrease in performances occurs as the rubber bearing of shoe or paint coating of girder deteriorates. For pier, the major mechanism for deterioration is assumed to be only corrosion. Thus the reduced performance of pier is expressed by the remaining section of reinforcement bars. The development of reinforcement corrosion is determined in accordance with Standard Specification for Design and Construction of Concrete in Japan.

5.2 Maintenance Methods

In order to prevent deterioration in structural performance, several options such as repair, restoring, and reconstruction are considered. Their applicability and effects on each component are shown in Table 19. Since the effects may differ even under the same conditions, average results are adopted here. Maintenance methods applicable to RC slab may vary according to the environmental conditions and are determined considering several assumptions.

Table 19. Effects of repair, restoring, and reconstruction

Structural component	Maintenance type	Average effect
Pier or Slab	Surface painting	Delays P_i decrease for 7 years
	Surface covering	Delays P_i decrease for 10 years
	Section restoring	Restores P_i to 1.0, and then allows it to deteriorate with the same slope as the initial deterioration curve
	Desalting (Re-alkalization)	P_i deteriorates with the same slope as the initial deterioration curve
	Cathodic protection	Delays P_i decrease for 40 years
	Section restoring with surface covering	Restores P_i to 1.0, delays P_i decrease for 10 years, and then P_i deteriorates with the same slope as the initial deterioration curve
Girder	Painting	Maintains initial performance until the end of the specified lifetime
Shoe	Replacement of bearing	Maintains initial performance until the end of the specified lifetime
Slab	Recasting	Maintains initial performance until the end of the specified lifetime
All	Reconstruction	Restore P_i to 1.0, delays P_i decrease for 10 years, and then P_i deteriorates with the same slope as the initial deterioration curve

5.3 LCC

LCC is defined as the total maintenance cost for the entire bridge group during its life. This is obtained by the summation of the annual maintenance costs through the service life of the bridges. The future costs are discounted to their present values. Other costs, such as indirect construction costs, general costs, administrative costs, etc., are calculated in accordance with Cost Estimation Standards for Civil Construction. The direct construction costs consist of material and labor costs and the cost of scaffold. The breakdown of the material and labor costs and the cost of the scaffold are shown in Tables 20 and 21. The construction costs are based upon the market prices.

Table 20. Material and labor costs

Maintenance action	Upper pier (yen/m^2)	Lower pier (yen/m^2)	Shoe (yen/part)	Girder (yen/m^2)	Slab -central section- (yen/m^2)	Slab -bearing section- (yen/m^2)
Surface painting	780,000	1,920,000	–	–	1,640,000	3,280,000
Surface covering	2,730,000	6,720,000	–	–	4,100,000	8,200,000
Section restoring	20,670,000	50,880,000	–	–	22,140,000	44,280,000
Desalting (Re-alkalization)	3,510,000	8,640,000	–	–	7,380,000	14,760,000
Cathodic protection	3,900,000	9,600,000	–	–	8,200,000	16,400,000
Section restoring with surface covering	22,620,000	55,680,000	–	–	26,240,000	52,480,000
Reconstruction	–	–	4,200,000	5,400,000	12,300,000	24,600,000

Table 21. Scaffold costs

Upper pier (yen/m^2)	Lower pier (yen/m^2)	Shoe (yen/part)	Girder (yen/m^2)	Slab -central section- (yen/m^2)	Slab -bearing section- (yen/m^2)
360,000	190,000	360,000	4,830,000	690,000	510,000

5.4 Application of MOGA to Maintenance Planning

It is desirable to determine an appropriate life-cycle maintenance plan by comparing several solutions for various conditions. A new decision support system is described here from the viewpoint of multi-objective optimization, in order to provide various solutions needed for the decision-making.

LCC, safety level and service life are used as objective functions. LCC is minimized, safety level is maximized, and service life is maximized. There are trade-off relations among the three objective functions. For example, LCC increases when service life is extended, and safety level and service life decrease due to the reduction of LCC. Then, multi-objective optimization can provide a set of Pareto solutions that cannot improve an objective function without making other objective functions worse.

In the present system, DNA structure is constituted as shown in Fig. 35, in which DNA of each individual consists of three parts such as repair method, interval of repair, and shared service life (Fig. 36). In this figure, service life is calculated as the sum of repairing years and their interval years. In Fig. 36, service life is obtained as 67 years which is expressed as the sum of 30 years and 37 years. The repair part and the interval part have the same length. Gene of repair part has ID number of repair method.

The interval part has enough length to consider service life. In this system, ID 1 means surface painting, ID 2 surface coating, ID 3 section restoring, ID 4 desalting (re-alkalization) or cathodic protection, and ID 5 section restoring with surface covering. DNA of service life part has a binary expression with six bits and its value is changed

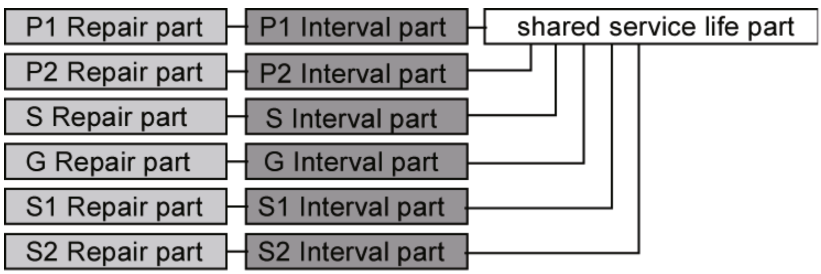

Fig. 35. Structure of DNA

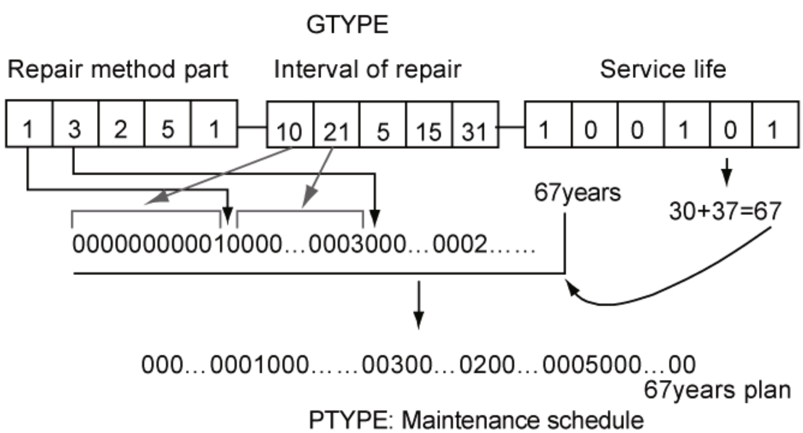

Fig. 36. Coding rule

to decimal number. For mutation, the system shown in Fig. 36 is used. Then, objective functions are defined as follows:

$$\text{Objective function 1:} \quad C_{total} = \sum LCC_i \rightarrow min \tag{12}$$

where LCC_i is LCC for bridge i.

$$\text{Objective function 2:} \quad Y_{total} = \sum Y_i \rightarrow max \tag{13}$$

subject to $Y_i > Y_{required}$, where Y_i is service life of bridge i, $Y_{required}$ is required service life.

$$\text{Objective function 3:} \quad P_{total} = \sum P_i \rightarrow max \tag{14}$$

subject to $P_i > P_{target}$, where P_{target} is target safety level.

The above objective functions have trade-off relations to each other. Namely, the maximization of safety level or maximization of service life cannot be realized without increasing LCC. On the other hand, the minimization of LCC can be possible only if the service life and/or the safety level decreases.

5.5 Three-Dimensional Graphical Systems

In order to find out several useful solutions from the set of Pareto solutions, a 3D graphical system was developed. The system aims to help the decision maker to select several solutions that satisfy some requirements through checking their constraint conditions by using JAVA3D. The system consists of three subsystems: 1) 3D representation, 2) general representation, and 3) graphical representation. Each representation is implemented using JAVA language.

The 3D representation system is the most important among the three subsystems. This system can select several candidates from the set of Pareto solutions by checking various requirements and express them in 3D graphics. In this study, both MOGA system and the 3D graphical system are written in JAVA so that the rendering of 3D graphs can be implemented in real time. Namely, the user can move the 3D graphs freely. It is very easy to move them by using a mouse. Any graph can be viewed from any direction by using the operations of extension, shrinkage, translation, and rotation. The 3D representation system can mainly implement the three actions: 1) emphasize the evaluation function, 2) emphasize a point, and 3) extract a range.

The general representation system can list the solutions obtained by the 3D representation system. The solutions can be arranged in the order of evaluation values. The solutions are listed up, corresponding to the range defined by MOGA system. While the 3D representation system is useful to grasp the relations and tendencies of solutions, the general representation system is useful to show the characteristics of each solution.

The graphical representation system can provide us with the detail of repair methods calculated by MOGA. The system can play a role in checking the appropriateness of the obtained repair methods and in finding out the tendency or pattern of repair program.

Observing and comparing the patterns obtained, it is possible to discover the branching points of short, medium and long term repair plans.

5.6 Application Example

Fig. 37 shows the Pareto solutions calculated by MOGA system. This graph is given in the conventional way of representation.

Fig. 38 shows the representation of the same graph by the proposed 3D representation system. Fig. 39 presents the same graph that is rotated and shrunken. As seen form Fig. 39, it is possible for the user to check the Pareto solutions from any desired direction by using the proposed representation system based on JAVA3D.

For example, it is possible to find out a gap among the solutions, which may be caused by the cost reduction by the common usage of scaffold. Apparently, it is possible to obtain more useful information by using the 3D representation instead of the usual 2D representation. Comparing the long term repair plans and short term repair plans, it is made clear that the long term plan is superior in monetary term to the plan with the repetition of short term repair (Table 22). The branching point between the short term plan and long term plan can be found out. Moreover, it is also possible to obtain the solutions for the cases in which the safety of the structure is emphasized and the LCC is emphasized, respectively. This means that the proposed system can provide the user with an appropriate solution for any case.

By considering LCC, safety level, and service life as objective functions, it is possible to obtain the relationships among these three performance indicators and provide

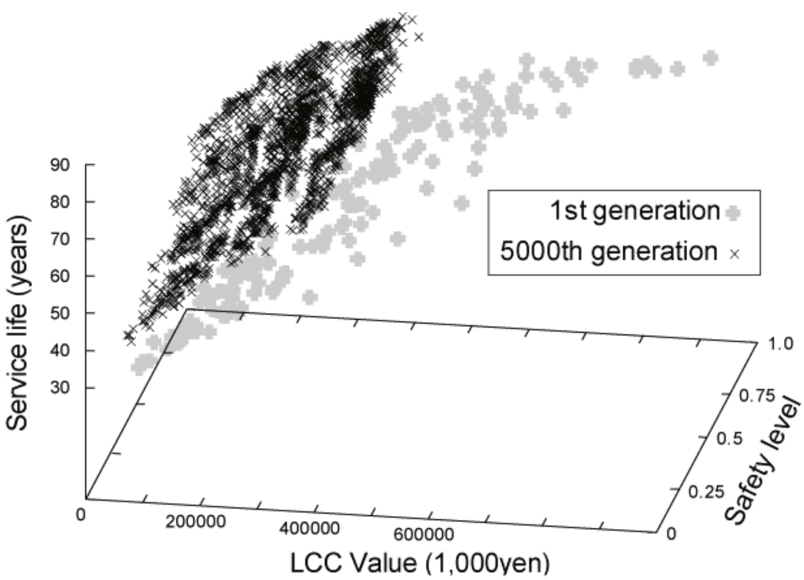

Fig. 37. Pareto solutions obtained by MOGA

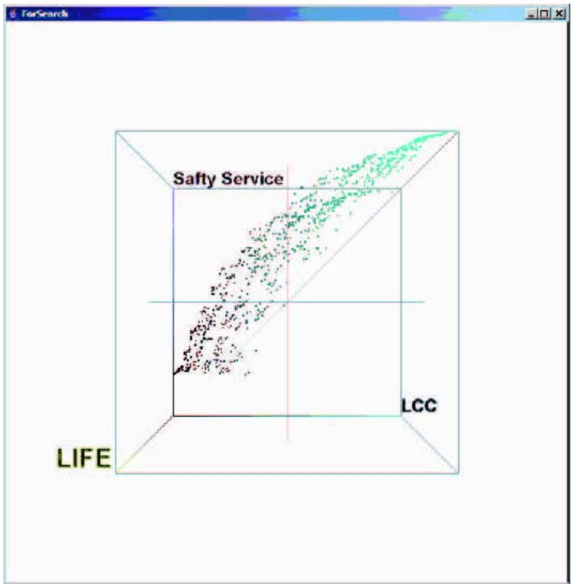

Fig. 38. JAVA 3D Application 1

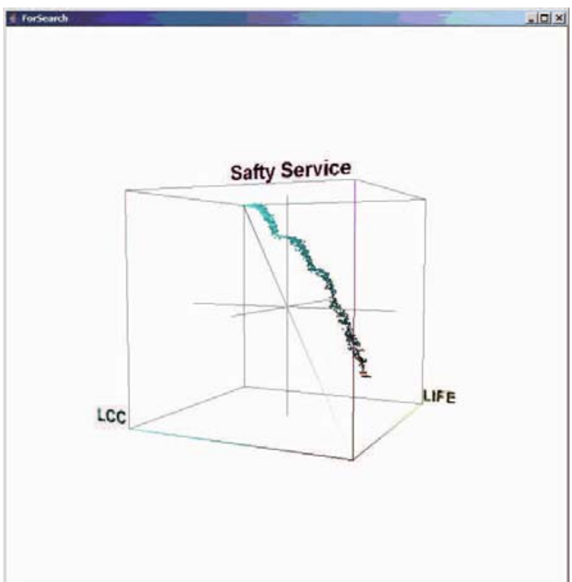

Fig. 39. JAVA 3D Application 2

Table 22. Maintenance terms

Maintenance term	LCC	Safety level	Service life
long term	359501	5.18887	84
middle term	308605	5.18132	66
short term	255104	5.18154	40

bridge maintenance management engineers with various maintenance plans with appropriate allocations of resources. Since the optimal maintenance problem is a very complex combinatorial problem, it is difficult to obtain reasonable solutions by the current optimization techniques. Although GA is applicable to solve multi-objective problems, it is difficult to apply it to large and very complex bridge maintenance problems. By introducing the technique of Non-Dominated Sorting GA-2 (NSGA2), it is possible to obtain efficient near-optimal solutions for the maintenance planning of a group of bridge structures. However, it is not easy for the decision maker to choose an appropriate solution from many Pareto solutions. In order to help the decision maker, a 3D graphical system is developed using JAVA techniques. It is important to find the appropriate repair methods and the branching points of cost effectiveness.

6 Conclusions

In this paper, several practical optimization methods including GA were introduced, which are based on "evolutionary computing" or "soft computing". Several application examples in structural engineering are presented to discuss the efficiency and applicability of the methods described here. Through the numerical computations, the following conclusions were derived:

1. The optimization problems in real life are very difficult to solve, because they have objective functions and constraint conditions which have uncertainty and vagueness.
2. The evolutionary computing including GA is useful in solving real life problems, because of their superior ability such as understandable thinking way, high searching performance, easiness of programming, and robustness to peculiar characteristics of problems.
3. The structural vibration control system presented in this paper has an advantage that it can adapt to the change of structural systems and environments. Through the model and numerical experiments, it was validated that the systems can follow the change of vibration characteristics of structure. Using the descent method for the learning in fuzzy reasoning, quick and right adaptation can be achieved.
4. A decision support system for the aesthetic design of bridge handrails can be applied for practical use. In order to obtain several satisfactory design alternatives, the immune algorithm was applied to the optimization procedure and the neural network was used for the learning of the necessary knowledge. The effectiveness of the system was confirmed through numerical calculations.

5. The optimal restoration scheduling was formulated as a multi-objective optimization problem. By considering restoring days, LCC and performance level as objective functions, it is possible to obtain the relationships among these three performance indicators and to compare feasible optional solutions obtained under various conditions.
6. An optimal maintenance planning problem was also formulated as a multi-objective optimization. Furthermore, a 3D graphical representation system was introduced to find out several useful solutions from the set of Pareto solutions obtained by the optimal maintenance planning system using Multi-Objective Genetic Algorithm (MOGA).
7. By comparing the method with the current methods, it was proven that the present method can reduce the computation time, improve the convergence of searching procedure, regardless of vague or uncertain objective functions and constraint functions.

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