Optimization of Rehabilitation Strategies for Concrete Bridges

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Summary

This study attempted to develop a decision support system for rehabilitation strategies of existing concrete bridges based on life cycle analysis. This proposed system is able to not only evaluate the serviceability of existing bridge members, but also offer some strategies based on a combination of maintenance cost minimization and quality maximization approach. For solving this optimization problem, the Genetic Algorithms were adopted. By applying these algorithms to the optimization problem, the approximation optimal solution (rehabilitation strategy) could be quickly found. Moreover, applications to some existing concrete bridges were presented so as to demonstrate the suitability of proposed bridge management system. As a result, it was verified that this proposed system is able to estimate the deterioration of bridge members and present various rehabilitation strategies.

Keywords: bridge management system(***J-BMS***); bridge rating expert system; concrete bridge; maintenance planning; genetic algorism; optimization

1. Introduction

Recently, due to such factors as the increase in traffic volume, the increase in the weights of vehicles and the structural aging, many highway bridges have seriously deteriorated over the years in many advanced countries. In Japan, one report shows that in about 10 years from now, around 2010, the ratio of the bridges which will reach 50 years of age will be about 35% since many highway bridges have been constructed through the national highway networks' project launched around 1955. Thus, it is essential that those bridges should be repaired or strengthened depending on the seriousness of their deterioration. Despite the problem, since the budget is limited, it is necessary for the funds to be split equally for both maintaining the deteriorated bridges and constructing the new ones. For this reason, the necessity of developing a practical bridge management system has been pointed out in Japan, because the maintenance of existing bridges has become a major social concern. The goal of this system is to assist the decision-makers and the administration in doing their job.

The aim of this study is to develop a practical bridge management system (***J-BMS***) for deteriorated concrete bridges, integrated with the Concrete Bridge Rating Expert System(***BREX***) [1,2] that can be used to evaluate the serviceability of existing concrete bridges. The proposed system uses multi-layered neural networks to predict deterioration processes in existing bridges, construct an optimal maintenance plan for repair and/or strengthening measures based on minimizing life cycle cost, and also estimate the maintenance cost. In this system, the Genetic Algorithm (GA) technique was used to search for an approximation of the optimal maintenance plan [3,4]. A comparison of the results of applying this system to some actual in-service bridges with the results of questionnaire surveys to experts shows found that optimal maintenance planning as well as bridge rating can be predicted accurately using this system.

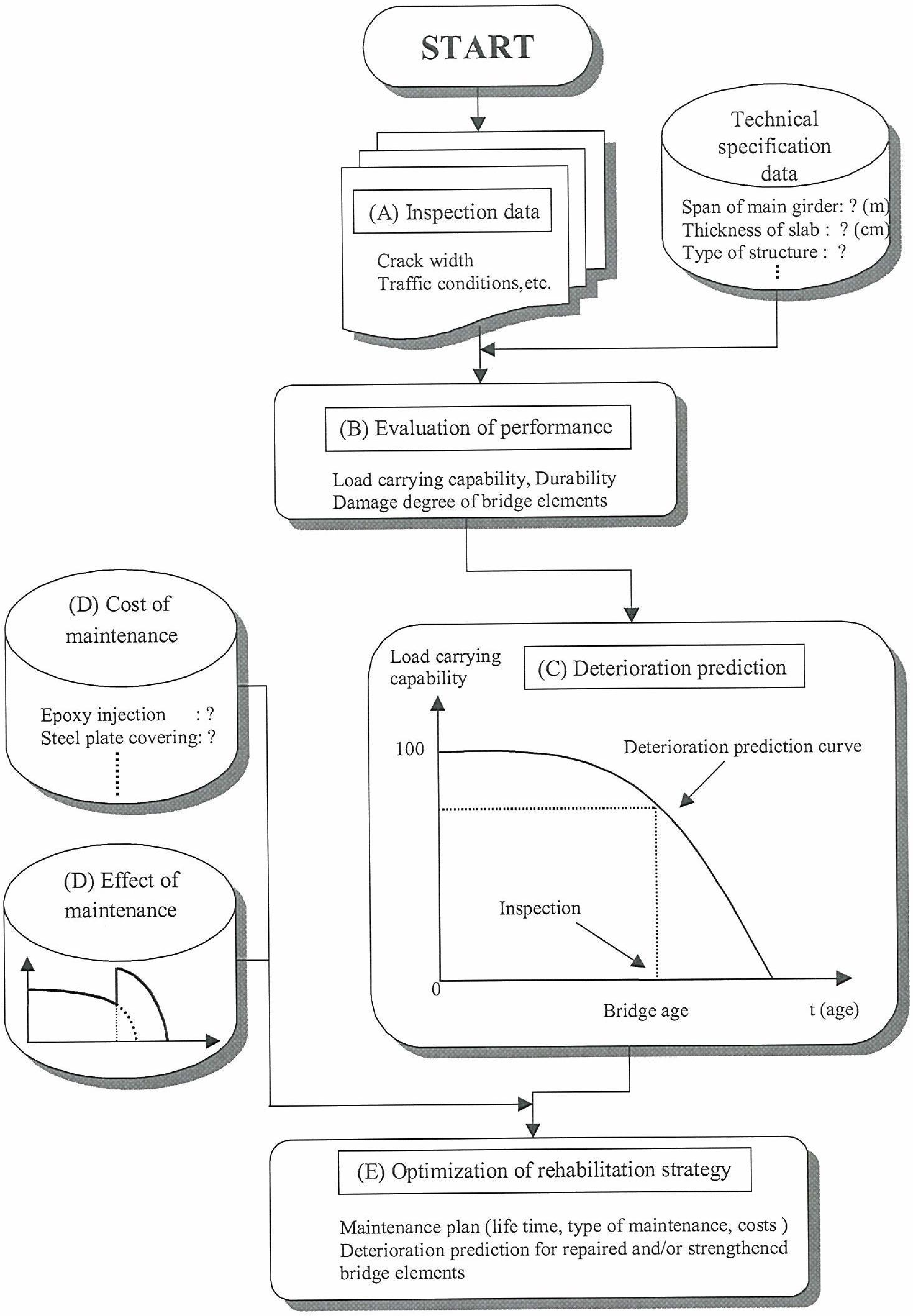


Fig. 1 Flow of J-BMS

2. Development of J-BMS

Figure 1 shows the flowchart of the proposed J-BMS. The J-BMS is applied mainly to the existing reinforced concrete bridges, and target members are main girders and slabs at present stage. The proposed J-BMS is constructed on a personal computer using the ***Visual Basic*** and ***C language***.

For existing concrete bridges, the first step in the proposed J-BMS involves a wide range visual inspection data related to the target bridge (A). Next, the performance of the bridge members is evaluated using the obtained inspection data and the technical specifications of the target bridge (B). This evaluation is performed using a program referred to as the Concrete Bridge Rating Expert System (***BREX***) which is currently under development by the present authors. The outputs of this evaluation include the mean soundness scores for load-carrying capability, durability, etc., which are given on a scale of 0-100 [5]. Then, based on the results of the expert system, present deterioration can be characterized and the remaining life of the bridge can be estimated using the predicted function of deterioration (C). As a preliminary step, the effect of repairs and strengthening were estimated, and the cost of each maintenance measure was determined, thereby enabling the estimation of maintenance costs and the prediction of remaining life after maintenance (D). Finally, if the present remaining life calculated by J-BMS does not exceed the expected service life, the rehabilitation strategy is obtained from the prediction curve according to the cost and effect of repairs and strengthening. This strategy includes various maintenance plans provided by the cost minimization or quality maximization (E).

2.1 Bridge Rating

The authors have been working for some time on the development of an expert system that can be used to evaluate the performance of existing concrete bridges based on knowledge and experience acquired from domain experts [1,2]. The proposed expert system (***BREX***) evaluates aspects of a bridge's present performance, such as serviceability, load-carrying capability, and durability. It is based primarily on information obtained from a wide range visual inspection data, such as traffic conditions, crack width, etc. though various performances such as serviceability, aesthetic, environmental, functionality, etc. are able to be mentioned as other indexes for evaluation of existing bridges. In the present study, it is also defined that this serviceability is estimated by load-carrying capability and durability. In addition, load-carrying capability is defined as the bridge performance based on the load-carrying capacity of the bridge member, and durability is defined as the ability of the bridge member to resist deterioration based on the deterioration speed of the member. Therefore, these two performances are applied as index to consider the necessity of maintenance for deteriorated bridges. In fact, load-carrying capability is applied as an index to estimate the necessity of strengthening works, and then durability is applied as an index to estimate the necessity of repair works in the proposed J-BMS.

2.2 Deterioration Prediction

The present performance of existing bridge members can be evaluated using the proposed expert system (***BREX***). However, this system cannot be used to estimate future deterioration of bridge members. Therefore, prediction curves for the load-carrying capability and durability, respectively, are used to perform deterioration estimation though various deterioration prediction methods such as transition probability matrix have been proposed in several other papers [6]. The following assumptions were made in constructing the deterioration prediction curves of the present study:

1) The deterioration curves for the bridge members are drawn as an integrated convex graph in which the vertical axes represent the mean soundness scores of load-carrying capability and durability and the horizontal axes represent bridge age due to the fact that deterioration progresses rapidly with bridge age. The mean soundness scores of load-carrying capability and durability obtained from the expert system are described below as $S_L(t)$ and $S_D(t)$, respectively[7,8].

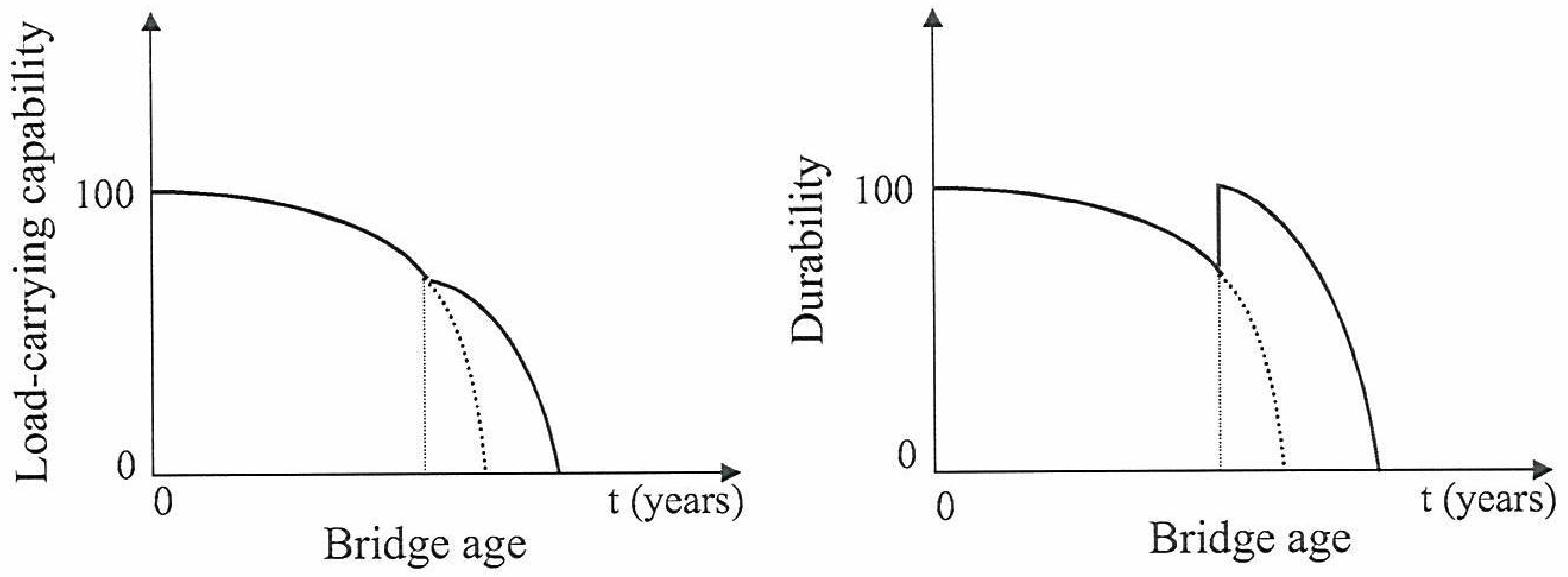
$$S_L(t)=f(t)=b_L-a_Lt^4 \quad (1) \qquad\qquad S_D(t)=g(t)=b_D-a_Dt^3 \quad (2)$$

where, a_L, b_L, a_D, b_D : constants, t : bridge age (years).

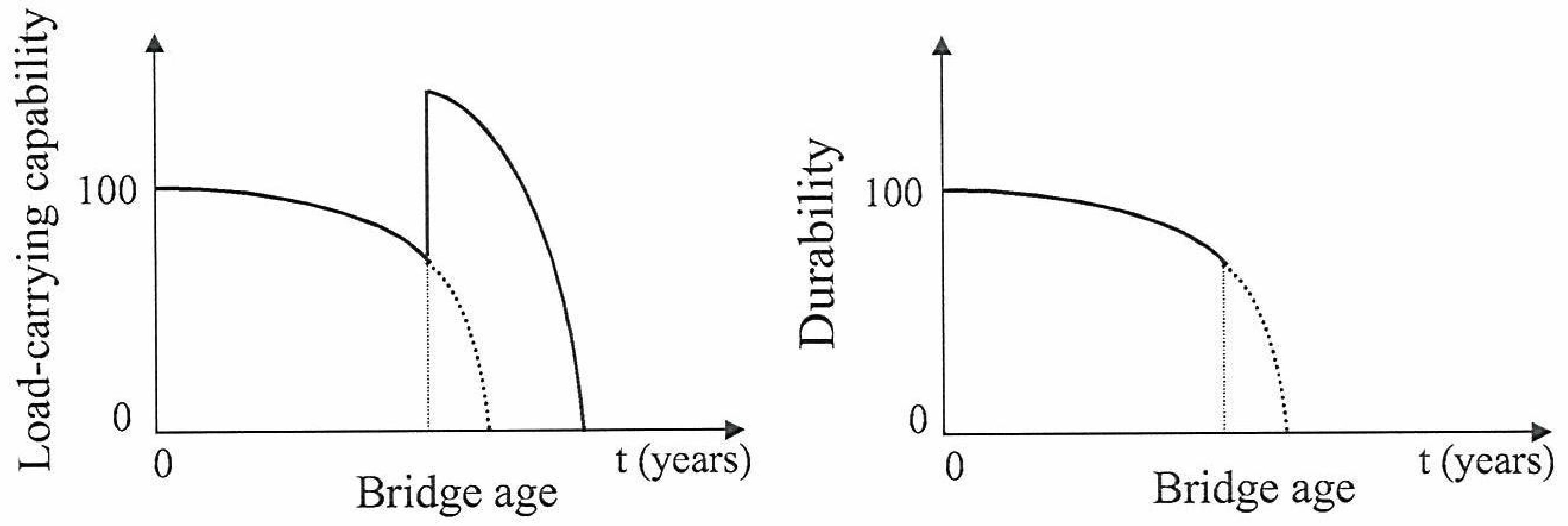
2) The mean soundness scores of load-carrying capability and durability are ranked on a scale of 0-100, on which a score of 100 represents a newly built bridge. As the bridge deteriorates, the score decreases and finally reaches 0, indicating that the bridge can no longer remain in service and requires rebuilding.
3) The deterioration curves up to the first inspection, that is, $f_{(0)}(t)$ and $g_{(0)}(t)$ are given by two elements: the score when the newly built bridge enters service (100) and the mean soundness score at first inspection, which is obtained using the expert system.
4) Repair and strengthening works influence the load-carrying capability and the durability of the bridge members. The deterioration curve after maintenance differs according to the type of maintenance performed.

2.3 Effect of maintenance

Although a new method has been presented which clarifies the effect of repair and/or strengthening works on the deterioration prediction curves of the load-carrying capability and the durability, this method can not be applied to conventional evaluation systems. In the present study, a repair work is assumed to affect the deterioration curve of durability, whereas strengthening work is assumed to affect the deterioration curve of load-carrying capability. Therefore, the basic concept of the strengthening effect is to show that the mean soundness score of the load-carrying capability would grade up if the bridge is strengthened, while the basic concept of the repair effect is to show that the mean soundness score of the durability would grade up and the velocity of the prediction curve for the load-carrying capability would also slow down (the deterioration speed of the load-carrying capability would slow down), if the bridge is repaired. The basic concept of this effect is depicted in Figure 2. Furthermore, the degrees of recovery of performance (load-carrying capability and durability) associated with repairs and/or strengthening as judged by an expert and comparing the present standard of design and the previous one were obtained and are listed in Table 1 and Table 2 [5]. In future studies, these tables should be modified using experimentally acquired data since the values presented here are strictly hypothetical.



(a) Effect of repair



(b) Effect of strengthening

Figure 2 Basic concept of maintenance effect

Table 1 Effect and cost of repair and strengthening measures for main girder

Maintenance measure	Type of maintenance	Load carrying Capability	Durability	Cost (1U□ a¥1,000/m^2)
Epoxy injection	R	*1	100	23.8U
Recovery of cross section	R	*1	100	14.0U
Glass cloth	R	No effect	*1	25.2U
Mortar spraying	R	No effect	*2	14.0U
Steel plate covering	S	See Table 2	70	112.5U
FRP covering	S	See Table 2	70	2 layers:112.5U 4 layers: 78.0U
External cables	S	See Table 2	No effect	150.U

Note: R = Repair, S = Strengthening, *1 : Deterioration rate reduced by 50%. *2 : Deterioration rate reduced by 60%

Table 2 Degree of recovery of load-carrying capability for strengthening measures

Year designed	Steel plate covering (FRP : 4 layers)	FRP covering (2 layers)	External cables
1939	130	120	150
1956	120	110	140
1956	100	100	100

2.4 Optimization of Rehabilitation Strategy

The proposed J-BMS estimates the remaining life of a target bridge in terms of durability and load-carrying capability after diagnosis of the present performance using the proposed expert system. In addition, if the present remaining life calculated using the deterioration curve is found to be shorter than that predicted by the expected service life (denoted by T), some maintenance plans are presented as the rehabilitation strategy based on life cycle costs, the prediction curve and the effects of repairs and/or strengthening measures. In the present study, maintenance planning is modeled as a combinatorial optimization problem, because the maintenance plan is comprised of various maintenance measures [5]. The analysis period begins from the present age of bridge (denoted by t') and runs until the expected service life (T). Note that even though T is the end of the analysis period, this point does not represent the end of the target bridge's life. In the present analysis, one maintenance measure is chosen every year in order to construct a maintenance plan. Thus, maintenance may include no maintenance (No repair, No strengthening) as well as combinations of repairs and/or strengthening measures.

Many aspects influence the choice of rehabilitation strategy. Therefore, the rehabilitation strategy should be optimized for budgets, damage, safety, policy, environment, road users etc. As a preliminary step, the present study only examines the direct-cost minimization of maintenance measures (see Eq. (3)) and the maximization of bridge quality (see Eq. (4)) as the optimization method. From a practical point of view, the quality of a bridge is defined as the total sum of the mean soundness scores of durability and load-carrying capability during the analysis period. Therefore, the present optimization problem of rehabilitation strategy is described by the following multi-objective combinatorial optimization:

$$\textbf{Objective:}\quad F_1 = \sum_{t=t'}^{T-1} C_{tj} \quad \rightarrow \quad \text{min} \qquad (3) \qquad F_2 = \sum_{t=t'}^{T} \{S_L(t) + S_D(t)\} \quad \rightarrow \quad \text{max} \quad (4)$$

$$\textbf{Subject to:}\ S_L(t) > 0 \qquad \mathrm{S_D}(t) > 0, \quad 0 \le t \le T$$

where, t=Bridge age (years), j=Type of maintenance measure chosen for the year t, t'=Present age of bridge (initial time, corresponding to the first year of the analysis period), T=Expected service life (final time, corresponding to the last year of the analysis period), $S_L(t)$=Mean soundness score of load-carrying capability in the year t, $S_D(t)$=Mean soundness score of durability in the year t, C_{tj}=Cost of maintenance measure j carried out in the year t, F_1=Total cost of maintenance measures, F_2=Total sum of mean soundness scores of load-carrying capability and durability during the analysis period, corresponding to bridge quality.

Since this is a multi-objective combinatorial optimization problem, GAs are adopted for the combinatorial problem due to the large number of combinations. GAs are used to search for an optimal maintenance plan. In addition, the ε-constraint method was applied to the multi-objective problem. In order to suggest various maintenance plans according to cost constraints that are established by the J-BMS user, the ε-constraint method is applied to the following algorithm for suggesting the rehabilitation strategy of a target member. In this case, F_1 is assumed to be prior to F_2, that is, cost minimization is more important than quality maximization (see Eqs. (3) and (4)). The procedure works with the following three main steps.

Step 1: The maintenance plan based on cost minimization is searched using GAs. Cost 1 and Quality 1 are obtained from this calculation, where Cost 1 = minimum cost, corresponding to the cost of the obtained maintenance plan and Quality 1 = quality of the maintenance plan obtained in this calculation.

Step 2: GAs are applied to the following problem and search for the optimal maintenance plan based on quality maximization. The additional budget α is established by the BMS user.

$$\textbf{Objective: } F_2 \rightarrow \max \quad (5) \qquad \textbf{Subject to: } F_1 \le \varepsilon = Cost1 + \alpha \quad (6)$$

where α = additional budget.

Step 3: Return to Step 2 after altering α. This repetition enables various maintenance plans to be suggested.

3. Optimization of Rehabilitation Strategies for Existing Bridges

In here, the J-BMS is applied to seven existing bridges (nine spans) which are all RC T-girder type bridges, in order to test its validity. In this example, the expected service life (T) of the target bridges was set to 90 years, the parameters used in the present application of GAs are shown in Table 3.

Table 3 Parameters of the genetic operator used in this study

Item	Parameter value or method
Population size	30 individuals
Max generation	300 generations
Selection method	Tournament selection and Elitist selection
Crossover method	one–cut-point crossover
Crossover rate	100%
Mutation rate	10%

Tables 4 shows, as an example, the results of the deterioration estimation of the main girders obtained in the form of outputs from the bridge management system (J-BMS). These results are system outputs reflecting learned weights obtained by using data for a number of bridges other than those covered in the deterioration estimation as training data for learning (leave-one-out method)[4]. In the leave-one-out method of learning used in this study, to estimate the deterioration of "Hataka-bridge span 1" for example, data on the eight spans other than the "Hataka-bridge span 1" are used for the training of the inference engine. Estimating the degree of deterioration of the only span whose data was not used for the learning by the above method is equivalent to estimating the deterioration of a newly encountered span after completing learning sessions for a number of spans.

Table 4 Estimation results obtained by using the deterioration estimation function (main girders)

Bridge name Judgment item	Hataka	Niji	Nobutaka	Mine	Mine	Getusyou	Tobimatu	Tobimatu	Ougame
Girder design	f-s(69.1)	M(60.8)	M(60.5)	f-s(68.4)	f-s(69.8)	f-s(71.4)	f-s(67.4)	f-s(64.2)	M(56.7)
Girder execution	f-s(65.2)	M(43.4)	f-s(75.9)	f-s(68.5)	f-s(68.7)	M(61.9)	M(62.0)	f-s(71.5)	f-s(68.5)
Service condition	f-s(70.1)	f-s(74.2)	f-s(73.2)	f-s(83.3)	f-s(82.0)	f-s(67.9)	f-s(69.6)	f-s(70.1)	f-s(69.5)
Deterioration of material	M(50.1)	M(39.1)	f-s(78.3)	f-s(64.6)	f-s(68.3)	f-s(71.2)	f-s(76.7)	M(38.4)	f-s(72.9)
Flexural cracking	M(58.9)	s-d(32.7)	M(58.2)	f-s(79.6)	f-s(81.4)	f-s(78.9)	f-s(79.1)	f-s(84.4)	f-s(82.3)
Shear cracking	S(92.2)	S(95.0)	S(92.7)	S(91.7)	S(91.7)	S(91.4)	S(92.1)	S(91.5)	S(91.4)
Corrosion cracking	M(49.5)	M(46.8)	f-s(84.3)	f-s(84.1)	f-s(65.2)	f-s(82.4)	S(89.0)	M(40.1)	f-s(73.9)
Bond cracking	S(91.6)	S(92.6)	S(91.0)	S(91.4)	S(91.6)	S(91.0)	S(91.2)	S(91.2)	S(91.2)
Overall damage	M(53.4)	M(49.9)	f-s(84.7)	f-s(75.6)	f-s(73.5)	f-s(80.4)	f-s(84.3)	M(37.6)	f-s(81.8)
Load-carrying capability	M(52.8)	f-s(64.3)	f-s(73.5)	S(91.4)	S(91.6)	f-s(65.0)	f-s(64.3)	M(51.7)	M(55.3)
Durability	M(49.9)	M(57.6)	f-s(84.2)	f-s(71.7)	f-s(68.5)	f-s(74.8)	f-s(79.9)	M(44.0)	f-s(78.1)
Serviceability	M(50.9)		f-s(78.7)	f-s(73.8)	f-s(76.5)	f-s(69.3)	f-s(75.4)	M(49.9)	f-s(68.3)
Overall error	84.4	200.5	97.3	54.2	68.4	129.4	67.8	143.9	110.0

Note: S: safe, f-s: fairly safe, M: moderate, s-d: slightly dangerous, D: dangerous

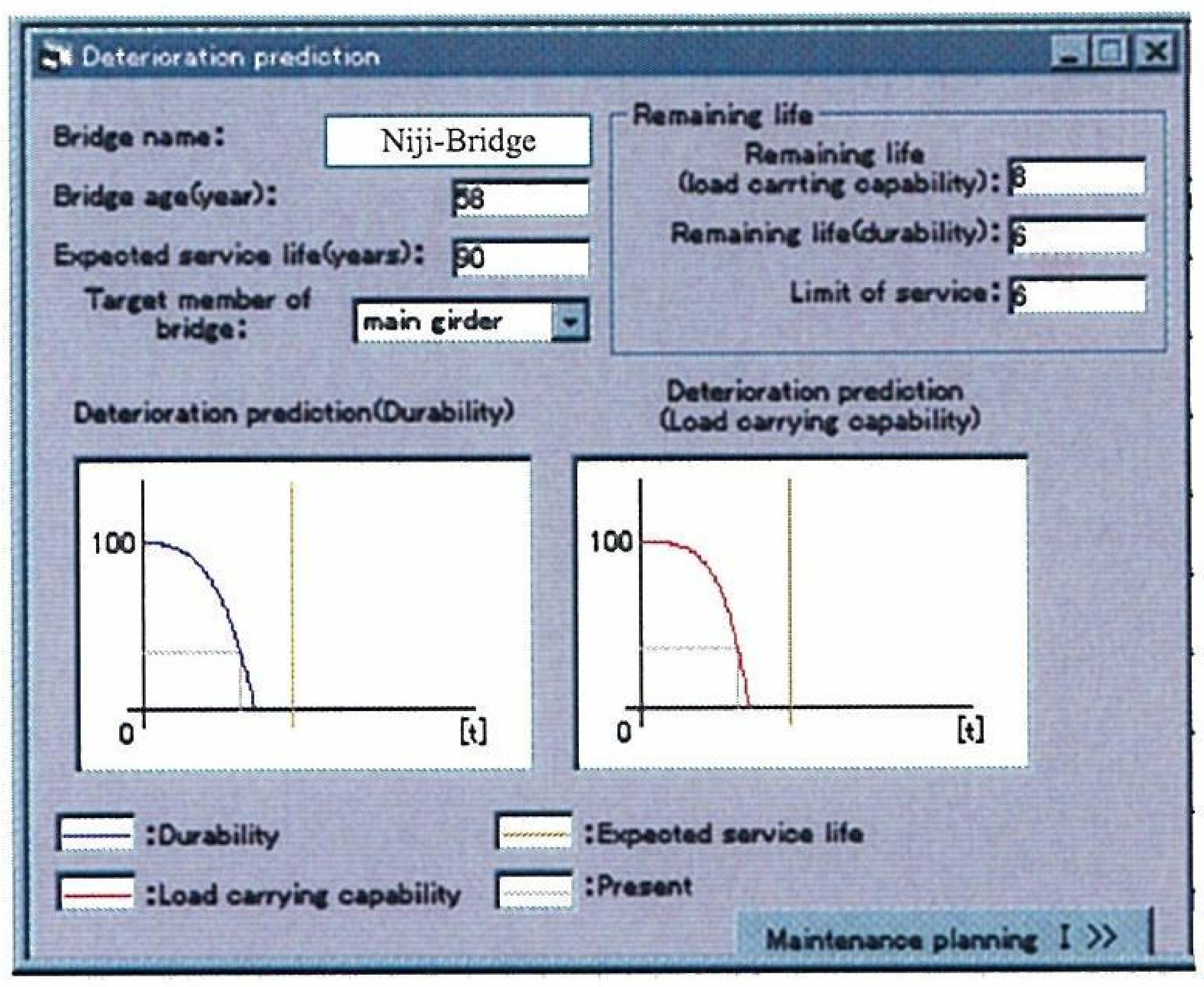
Next, based on the above-mentioned estimation results from the BREX, the proposed J-BMS is applied to an existing bridge, the Niji-bridge as an example, in order to demonstrate the validity of J-BMS. The Niji-bridge is a reinforced concrete T-girder-type bridge. In this example, the expected service life (*T*) of the target bridge has been set to 90 years for both girders and slabs. In the proposed J-BMS, the target bridge data, such as the technical specifications and inspection data for the Niji-bridge main girder are first entered into the computer. Using these data, the J-BMS evaluates the present performance of the bridge. The expected service life, as established by the J-BMS user, is then input into the system. In this example, the expected service life (*T*) of target bridge was set to 90 years. After that, the J-BMS estimates the present deterioration and remaining life of target bridge with respect to load-carrying capability and durability. In here, as an example, maintenance planning for the Niji-bridge main girder is considered. Figure 3(a) shows a deterioration prediction screen output for the main girder of Niji-bridge span 6. The upper right section indicates the present remaining life with respect to load-carrying capability and durability. The lower section illustrates the graphs of the deterioration prediction curves for load-carrying capability and durability. These outputs show that the present remaining life does not exceed the expected service life, namely, 90 years. If the present remaining life calculated using the J-BMS does not exceed the expected service life, the maintenance plan is generated based on the direct-cost minimization approach. Then the J-BMS user can establish the required additional budget based on the results provided by the direct-cost minimization. Then, by inputting various additional budgets, this system shows a variety of maintenance plans based on bridge quality maximization and taking into account the cost constraints, i.e., the sum of the minimum costs and the additional budget. The screen indicates that service life, both in terms of load-carrying capability and durability, cannot be fulfilled unless a maintenance measure of one kind or another is taken. Figure 3(b) shows a maintenance plan needed to make the expected service life of 90 years possible while meeting the requirement of cost minimization. This plan involves the attachment of two layers of FRP sheet covering or of steel plating as a remedy to be implemented early in the service life, showing agreement with the remedies recommended by the domain experts [5]. Figure 3(c) shows a screen that shows load-bearing-capacity- and durability-based deterioration predictions and the remaining service lives in the case the suggested maintenance measure shown in Figure 3(b) has been taken. The table indicates that the suggested maintenance measure will enable the bridge to fulfil the expected service life. Figure 4(b) shows a maintenance plan drawn up so that the requirement of quality maximization is satisfied by increasing the cost under the plan of Figures 3(b) and 3(c). The modified plan is based on the upper limit of cost of 200U (U is calculated using the conversion rate of 1U=\1,000/m^2) and includes repair, which was not included in the plan of Figures 3(b) and 3(c). Thus, as comparison between Figures 3(c) and 4(c) reveals, the quality index has increased from 4715(58.9%) to 5266(65.8%), indicating that the bridge can be maintained with a higher margin of safety.

4. Conclusions

The conclusions of this study can be summarized as follows:

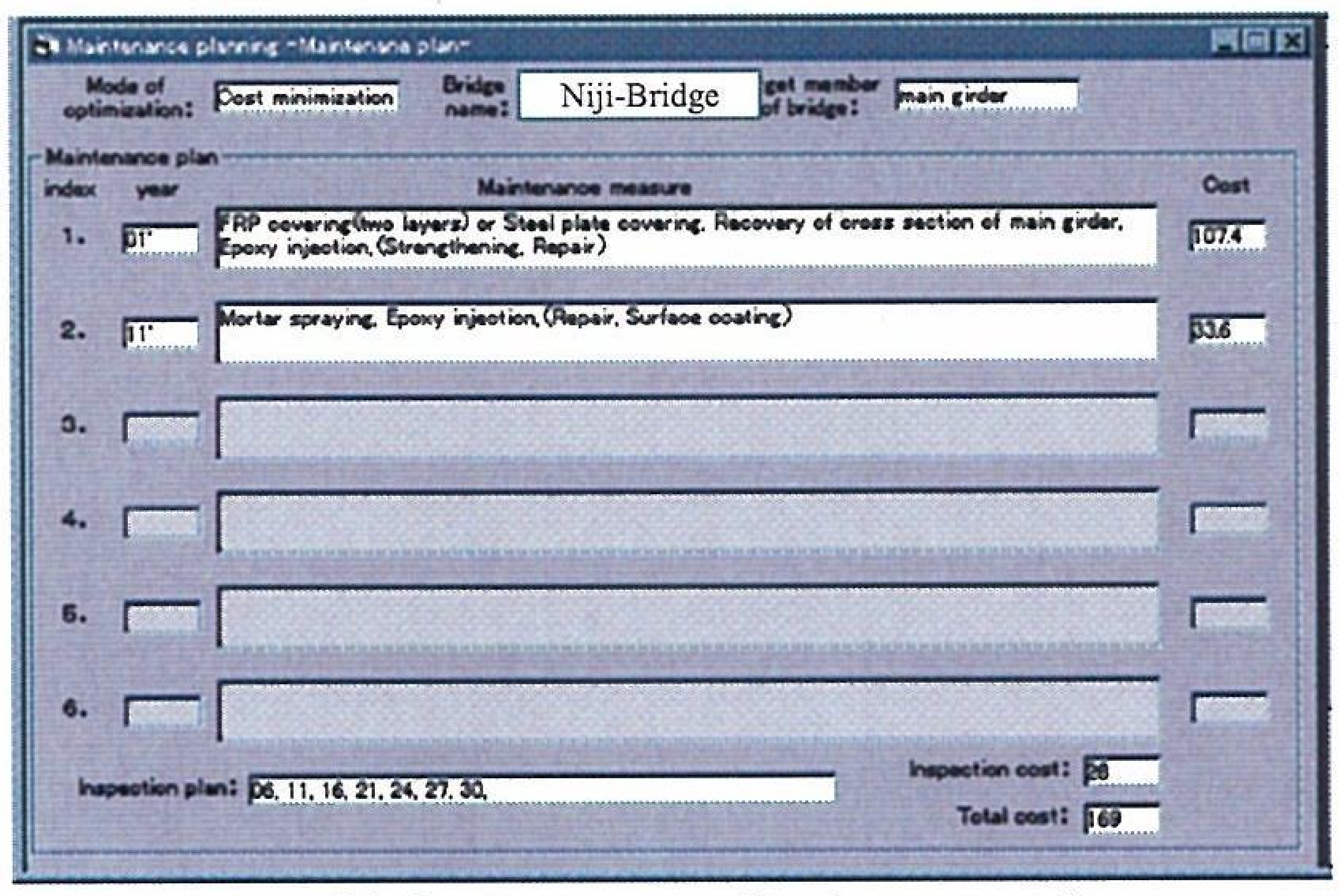
1) In order to clarify the difference between repairs and strengthening measures, It was decided to apply load-carrying capability and durability as the respective main indexes of performance for bridge members.
2) The deterioration curve was used to estimate the progressive deterioration of performance of existing bridge members. By assuming functional deterioration, the proposed BMS (J-BMS) is able to estimate the deterioration of the repaired and/or strengthened bridge members, and also to display the deterioration on a screen.
3) The proposed J-BMS was applied to an existing bridge. The authors verified that this BMS is able to estimate the deterioration of bridge members and present various maintenance plans based on cost minimization and also quality maximization using GAs. GAs are thus a powerful tool for obtaining an optimal maintenance plan.

Cost Minimization



Bridge name: Niji-Bridge
Bridge age(year): 58
Expected service life(years): 90
Target member of bridge: main girder
Remaining life
Remaining life (load carrting capability): 8
Remaining life(durability): 6
Limit of service: 6

(a) Output screen of prediction of deterioration

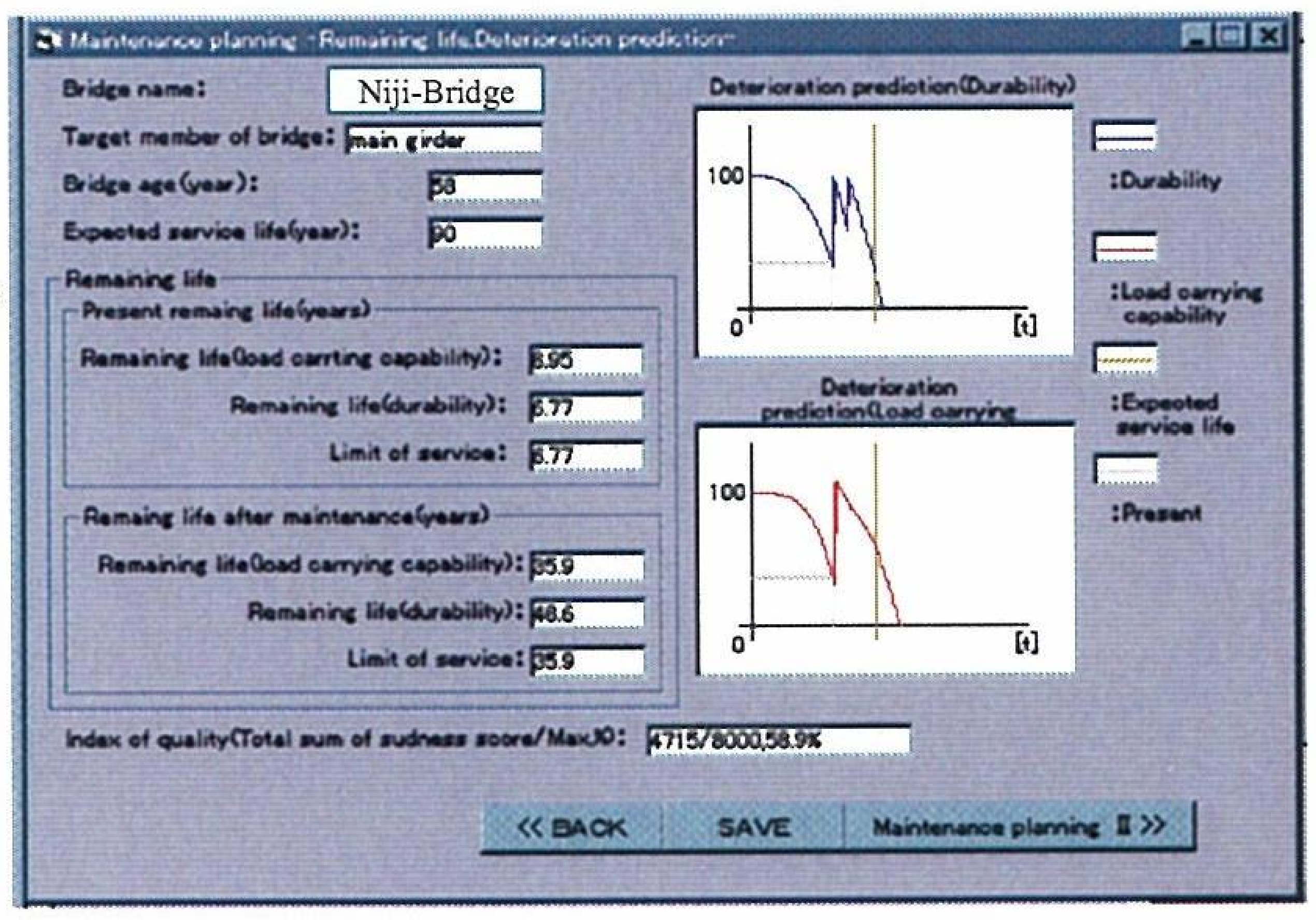


Mode of optimization: Cost minimization
Bridge name: Niji-Bridge
get member of bridge: main girder

index	year	Maintenance measure	Cost
1.	01'	FRP covering(two layers) or Steel plate covering, Recovery of cross section of main girder, Epoxy injection,(Strengthening, Repair)	107.4
2.	11'	Mortar spraying, Epoxy injection,(Repair, Surface coating)	33.6
3.			
4.			
5.			
6.			

Inspection plan: 06, 11, 16, 21, 24, 27, 30,
Inspection cost: 28
Total cost: 169

(b) Output screen of maintenance plan



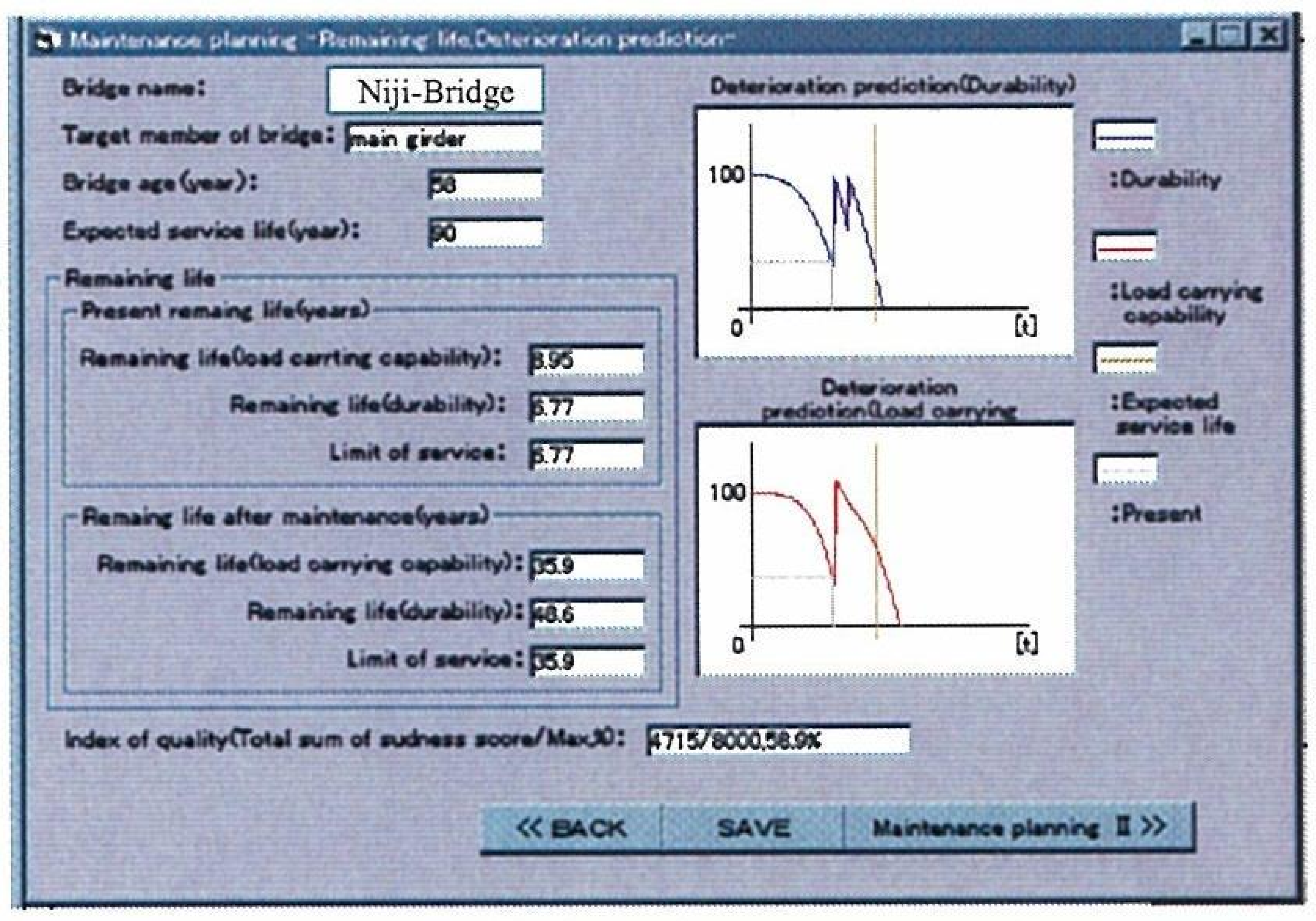
Bridge name: Niji-Bridge
Target member of bridge: main girder
Bridge age(year): 58
Expected service life(year): 90
Remaining life
Present remaing life(years)
Remaining life(load carrting capability): 8.95
Remaining life(durability): 6.77
Limit of service: 6.77
Remaing life after maintenance(years)
Remaining life(load carrying capability): 35.9
Remaining life(durability): 48.6
Limit of service: 35.9
Index of quality(Total sum of sudness score/Max)0: 4715/8000,58.9%

Cost : 169 Unit
Index of quality : 4715;58.9%

(c) Output screen of prediction of deterioration after maintenance

Fig. 3 J-BMS output screen for main girder of Niji-Bridge span 6 (Cost Minimization)

Quality Maximization


Maintenance planning -Remaining life,Deterioration prediction-

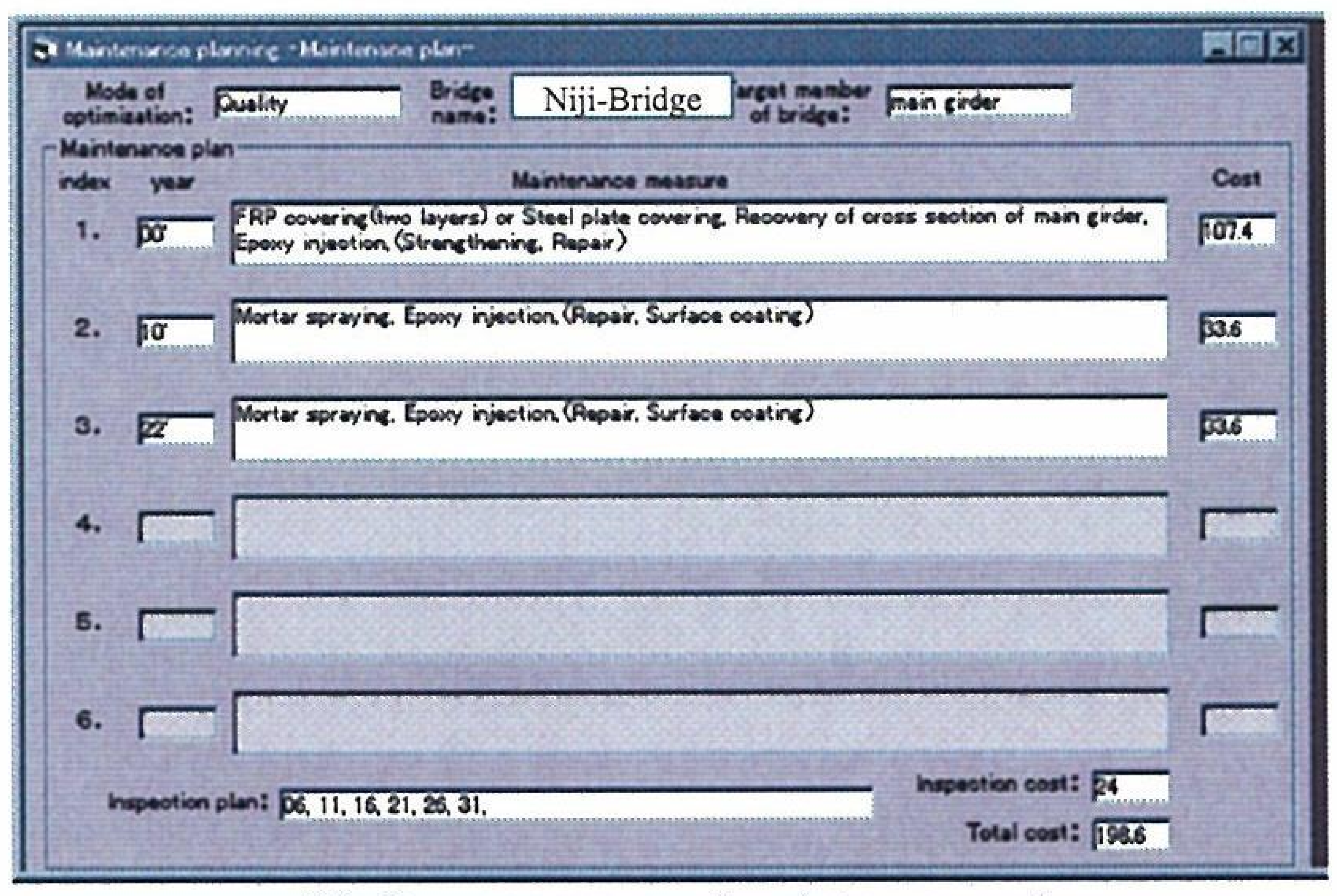
Bridge name: Niji-Bridge
Target member of bridge: main girder
Bridge age(year): 58
Expected service life(year): 90

Remaining life
Present remaing life(years)
Remaining life(load carrting capability): 8.95
Remaining life(durability): 6.77
Limit of service: 6.77

Remaing life after maintenance(years)
Remaining life(load carrying capability): 35.9
Remaining life(durability): 48.6
Limit of service: 35.9

Index of quality(Total sum of sudness score/Max.)0: 4715/8000,58.9%

(a) Output screen of prediction of deterioration under cost minimization


Maintenance planning -Maintenance plan-

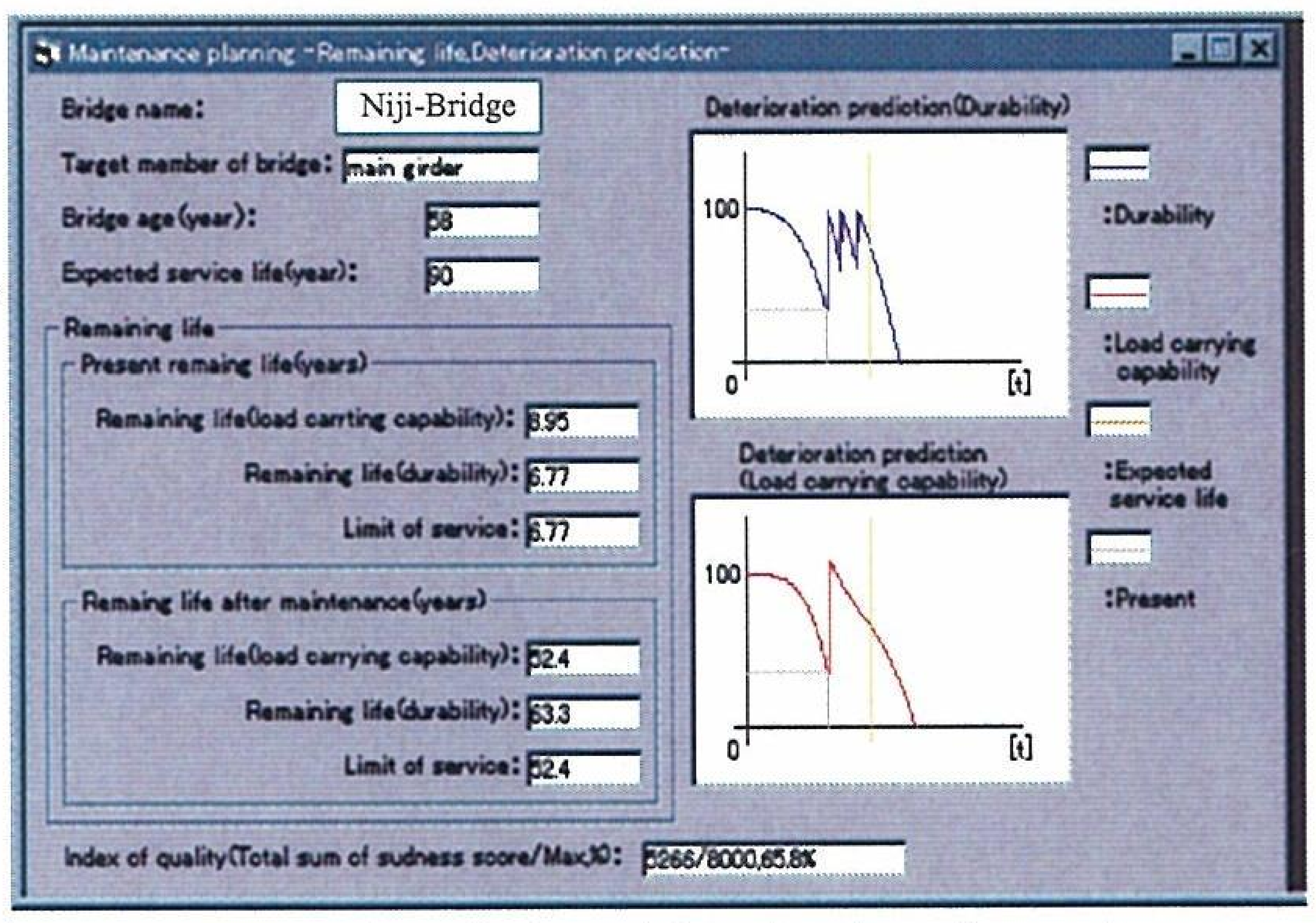
Mode of optimization: Quality
Bridge name: Niji-Bridge
Target member of bridge: main girder

Maintenance plan

index	year	Maintenance measure	Cost
1.	00	FRP covering(two layers) or Steel plate covering, Recovery of cross section of main girder, Epoxy injection,(Strengthening, Repair)	107.4
2.	10	Mortar spraying, Epoxy injection,(Repair, Surface coating)	33.6
3.	22	Mortar spraying, Epoxy injection,(Repair, Surface coating)	33.6
4.			
5.			
6.			

Inspection plan: 06, 11, 16, 21, 26, 31,
Inspection cost: 24
Total cost: 198.6

(b) Output screen of maintenance plan


Maintenance planning -Remaining life,Deterioration prediction-

Bridge name: Niji-Bridge
Target member of bridge: main girder
Bridge age(year): 58
Expected service life(year): 90

Remaining life
Present remaing life(years)
Remaining life(load carrting capability): 8.95
Remaining life(durability): 6.77
Limit of service: 6.77

Remaing life after maintenance(years)
Remaining life(load carrying capability): 52.4
Remaining life(durability): 53.3
Limit of service: 52.4

Index of quality(Total sum of sudness score/Max.)0: 5266/8000,65.8%

Cost : 198.6 Unit less than 200 Unit
Index of quality : 5266; 65.8%

(c) Output screen of prediction of deterioration after maintenance

Fig. 4 J-BMS output screen for main girder of Niji-Bridge span 6 (Quality Maximization)

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