Cost Optimization of Bridge Maintenance Using Genetic Algorithm

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Summary

Maintenance is critical to ensure that bridges are not structurally deficient or functionally obsolete. By optimizing the maintenance activities under limited maintenance resources, the bridges are kept in good conditions for service and the conditions can be improved. In this research, taking the bridge deck as an example, the cost optimization procedure for the long-term network-level maintenance strategies are presented using genetic algorithm. The feasibility of this approach is demonstrated using a real-world bridge system.

1. Introduction

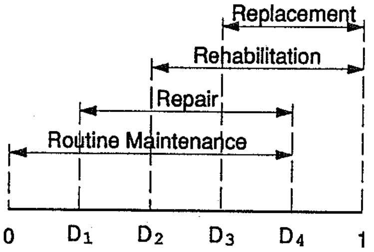
According to the *White Paper on Construction* [1], the maintenance cost of the social infrastructure in Japan will increase to 50% of total public works investment by 2020. Since it is impossible to check all bridges in detail every year and the maintenance budget is limited, there is a growing interest in the cost optimization of long-term maintenance strategy of bridges. However, this optimization is a challenging task because the number of possible combinations increases exponentially with the number of bridges, the planning period, and the number of maintenance methods. In this research, using the bridge deck as an example, a genetic algorithm (GA) is developed for this optimization purpose.

2. Deterioration Condition and Maintenance Method

In this paper, four maintenance methods are available and defined as follows. (1) *Routine maintenance* consists of the tasks that can not change the deck structure and function such as cleaning and removing snow and ice timely; (2) *Repairs* are those activities that can be performed with only partial traffic closure such as patching and sealing; (3) *Rehabilitation* involves major repair requiring special efforts and sometimes closure of the bridge to traffic such as attaching additional longitudinal girders or steel plates; and (4) *Replacement* is defined as a complete replacement of the bridge deck such as replacing the concrete deck by a steel one. It is assumed that only one of these four methods is carried out for one bridge at the beginning of every year, and rehabilitation or replacement will take place at most once in 5 years. According to the results of inspection, the conditions of bridge decks are assessed to be one of five deterioration levels as shown in column (1) of Table 1. Each level is quantified to be a value between 0 and 1 called deterioration degree D as shown in column (2). The condition description of each level is shown in column (3). The deck maintenance method of a bridge at one year is randomly selected according to the deterioration degree as shown in Fig. 1. Four example cases are given in this figure and will be discussed below. For instance, in the first case, if the deterioration degree is between 0.3 (D_2) and 0.5 (D_3) at the end of the second year, the possible maintenance method at the third year is routine maintenance, repair, or rehabilitation.

Level (1)	Degree D (2)	Description (3)
I	$0.8 \sim 1.0$	Potentially hazardous
II	$0.6 \sim 0.8$	Functionally or structurally inadequate
III	$0.4 \sim 0.6$	Functionally and structurally adequate
IV	$0.2 \sim 0.4$	Good condition
OK	$0.0 \sim 0.2$	Like new

Table 1. Deterioration Condition



Example Cases

No.	D_1	D_2	D_3	D_4
1	0.2	0.3	0.5	0.7
2	0.2	0.4	0.6	0.8
3	0.2	0.5	0.7	0.8
4	0.4	0.6	0.7	0.8

Fig. 1. Range of Deterioration Degree for each Maintenance Method

3. Deterioration and Cost Models

3.1 Deterioration Model

In this paper, a linear deterioration model considering the initial conditions, the yearly deterioration rates, and the maintenance impacts is adopted as follows [2]:

$$D(t) = D(0) + \sum_{j=1}^{t} \mu \times R(A_j, Tr_j) - \sum_{j=1}^{t} I_m(j) \tag{1}$$

where, $D(t)$ is the deck deterioration degree of a bridge at the end of year t. $D(0)$ is the initial deterioration degree at the beginning of the planning period. $R(A_j, Tr_j)$ is the yearly deterioration rate of a concrete bridge deck at year j and is changeable with the deck age A_j and the traffic coefficient Tr_j as shown in Table 2. Here, A_j is the number of years from the deck construction or replacement year to the maintenance year. Tr_j is the ratio between the predicted maximum traffic volume and the design traffic volume. The factor μ reflects the deterioration property of material. In this paper, 1.0 and 1.1 are applied for the concrete and steel decks, respectively. $I_m(j)$ is the impact on the deck deterioration degree due to the maintenance activity m at year j as shown in column (3) of Table 3. The column (2) of Table 3 shows an example of the deterioration degree range. A further study on these ranges is illustrated in Section 5.

Traffic coefficient Tr_j (1)	Bridge age A_j (Years) $0 \sim 10$ (2)	$10 \sim 20$ (3)	$20 \sim 30$ (4)	$30 \sim 40$ (5)	> 40 (6)
≤ 1.0	0.000	0.020	0.025	0.030	0.035
$1.0 \sim 1.1$	0.020	0.025	0.030	0.035	0.040
$1.1 \sim 1.2$	0.025	0.030	0.035	0.040	0.045
> 1.2	0.030	0.035	0.040	0.045	0.050

Table 2. Yearly Deterioration Rate $R(A_j, Tr_j)$

3.2 Maintenance Cost

The yearly deck maintenance cost of a bridge is calculated using the deck area and the unit cost of the selected maintenance method. The maintenance cost C of a bridge system over the planning period is determined at the beginning of the planning period by

$$C = \sum_{i=1}^{N} \sum_{t=1}^{T} ((1+r)^{-t} \times c_m(i,t) \times L(i) \times W(i)) \tag{2}$$

where N is the number of bridges; T is the length of the planning period; r is the discount rate that is assumed to be constant during the planning period; $c_m(i,t)$ is the unit cost of maintenance method m used for bridge i at year t. The unit costs are based on engineering experience only and have near linear relationship with the maintenance impacts as shown in Table 3. $L(i)$ and $W(i)$ indicate the length and width of bridge i, respectively.

Maintenance method (1)	Deterioration degree (2)	Impact (3)	Unit cost (Yen/m^2) (4)	*GA* code (5)
Routine maintenance	0.0 ~ 0.8	0.01	500	00
Repair	0.2 ~ 0.8	0.05	2500	01
Rehabilitation	0.4 ~ 1.0	0.40	20000	10
Replacement	0.6 ~ 1.0	0.90	40000	11

Table 3. Parameters of Maintenance Methods

3.3 Penalty Costs and Objective Function

The maximum allowable deterioration degree of a bridge deck is given only according to its age, and abbreviated as $D_{max}(A_t)$. Table 4 shows several cases that present $D_{max}(A_t)$ for every age range. The constraints on $D_{max}(A_t)$ and the maintenance budget B are considered as penalty costs. The penalty is zero if the constraints are satisfied. The objective function Z is the sum of maintenance cost and penalty costs:

$$Z = C \times (1 + p_1 \times \sum_{i=1}^{N} \sum_{t=1}^{T} \frac{D(i,t) - D_{max}(A_t)}{D_{max}(A_t)} + p_2 \times \frac{C-B}{B}) \tag{3}$$

where $D(i,t)$ is the deterioration degree of bridge i at year t. The two penalty costs are given importance weights of p_1 and p_2 for the deterioration degree and budget penalties, respectively. However, in this paper, the values of $p_1 = p_2 = 1$ are used. In addition, the deck replacement will not be adopted for a bridge that is assessed in deterioration levels I and II, and deck rehabilitation will not be adopted for a bridge in deterioration level I.

D_{max} Case No. (1)	Bridge age A_j (Years)				
	0 ~ 10 (2)	10 ~ 20 (3)	20 ~ 30 (4)	30 ~ 40 (5)	> 40 (6)
1	0.40	0.45	0.50	0.55	0.60
2	0.45	0.50	0.55	0.60	0.65
3	0.50	0.55	0.60	0.65	0.70
4	0.55	0.60	0.65	0.70	0.75
5	0.60	0.65	0.70	0.75	0.80

Table 4. Maximum Allowable Deterioration Degrees

4. Maintenance Strategy Optimization Using GA

The flowchart illustrating the *GA* implemented in this study is shown in Fig. 2. The three numbered modules are the main processes of the *GA* and are illustrated as follows.

4.1 Code Design and Population Production of Initial Generation

Because four maintenance methods are available, the basic string unit of maintenance method must be represented by two binary values as shown in column (5) of Table 3. The code structure is designed as shown in Fig. 3. The final string consists of many substrings representing all bridges in a given order. In a substring, every basic string unit represents the maintenance method at one year. Furthermore, every basic string unit of a substring depends on the bits of the previous years and partially decides the bits of the following years. Finally, the two codes of every basic string unit are generated simultaneously and selected semi-randomly from the possible maintenance methods.

4.2 GA Operators

The selection operator is that the maintenance strategies whose objective function values are equal to or less than the average objective function value of the generation may survive and those strategies with greater values are eliminated. Multi-point crossover is introduced within every substring so that the number of the crossover points is same as the number of bridges. Once the crossover points are randomly selected, the parts to the left of the crossover point in substrings are retained and the parts to the right are exchanged. To ensure that the new strings express feasible maintenance strategies, the substrings to the right of the crossover point are verified and regenerated if necessary. Similarly, with a probability of mutation, one basic string unit is altered into another within every substring. The substrings to the left of the mutation position are retained, the two bits at the mutation position are mutated with the feasible values, and the substrings to the right are verified.

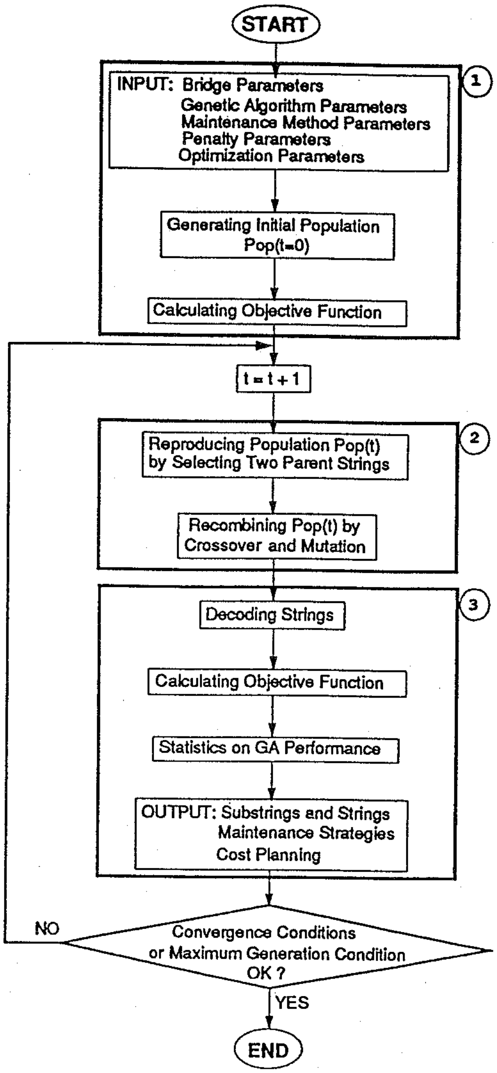


Fig. 2. Flowchart of the GA Procedure

Bridge:	$i-1$			i					$i+1$		
Method:	...	m_{T-1}	m_T	m_1	m_2	...	m_{T-1}	m_T	m_1	m_2	...
String:	...	1 0	0 1	1 1	0 0	...	0 1	1 0	0 1	1 0	...

Fig. 3. Coding Structure for Maintenance Strategy of Bridge Decks

4.3 Decoding and Evaluation

After the creation of every generation, by decoding the strings of a population, the maintenance strategies for all bridges are obtained. From these strategies, the number of bridges and areas of every maintenance method at every year are found, and maintenance costs and penalty costs are calculated. After many generations, the maintenance strategy with the minimum value of the objective function will represent a near-optimum solution.

5. Numeric Example and Discussion

To examine the above approach, the data of 287 bridges (269 with concrete decks, and 18 with steel decks) are obtained from Nagoya City bridge inspection database. The period of maintenance planning is taken as 5 years in accordance with the maintenance planning of other infrastructures in Japan. The deck maintenance budget and the maximum allowable deterioration degree are assumed to be 800 Million Yen and 0.8 (case 5 in Table 4), respectively. The discount rate is assumed 1.75% per year during the planning period.

A sensitivity analysis is done to check the effects of the population size Pop_s, the crossover probability P_c, and the mutation probability P_m. It is found that a moderate population size (50), a high crossover probability (80%), and a low mutation probability (0.1%) are good for this *GA* performance considering the convergence requirement and calculation time [3]. Taking the mutation probability as an example, its effect on the optimization procedure is shown in Fig. 4. Using Pop_s=50 and P_c=80%, if the mutation probability P_m is high, such as 10%, the minimum objective function values fluctuate because too many bits are mutated in every string. On the contrary, the convergence does not approach a good value for a too low P_m such as 0% or 0.01%. The value of P_m=0.1% gives better results than other P_m values.

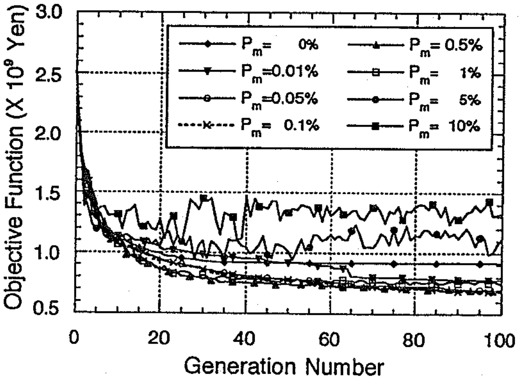


Fig. 4. Effect of Mutation Probability $(Pop_s = 50, P_c = 80\%)$

This *GA* optimization can help the bridge decision maker determine the trade off between maintenance budget and the deterioration. This can be done by changing the maximum allowable deterioration degree. Fig. 5 shows the values of the objective function of the near-optimum strategy for the five cases of $D_{max}(A_t)$ as shown in Table 4. Three maintenance budgets of $B_1 = 600, B_2 = 700$, and $B_3 = 800$ Million Yen are used for the planning period of five years. It is found that for a given $D_{max}(A_t)$, the minimum maintenance costs are near for different maintenance budgets. Furthermore, the maintenance cost decreases as the value of $D_{max}(A_t)$ increases. For $D_{max}(A_t) \geq 0.7$, the value of the maintenance cost converges to a fixed value (about 680 Million Yen). This means that 0.7 is a reasonable upper limit for the assumed impacts and unit costs of the maintenance methods. If the maintenance policy is to spend the whole budgets of 700 and 800 Million Yen, the maximum allowable deterioration degrees are about 0.70 and 0.67, respectively. Another method to control the maintenance cost is by revising the deterioration degree ranges of maintenance methods as shown in Fig. 1. Fig. 6 shows that the four example cases of deterioration degree ranges need different maintenance costs, budget penalty cost, and deterioration degree penalty cost. In the optimization procedure, the maintenance budget and maximum allowable deterioration degree are assumed to be 800 Million Yen and 0.6 (case 1 in Table 4), respectively. The decision maker can select the best case according to the available budget and deterioration degree penalty cost. In these example cases, cases 1 and 2 need much higher costs. Case 3 needs about 961 Million Yen and involves comparatively small penalty costs. In case 4, the maintenance cost is about 758 Million Yen. However, the deterioration degree penalty cost is too large.

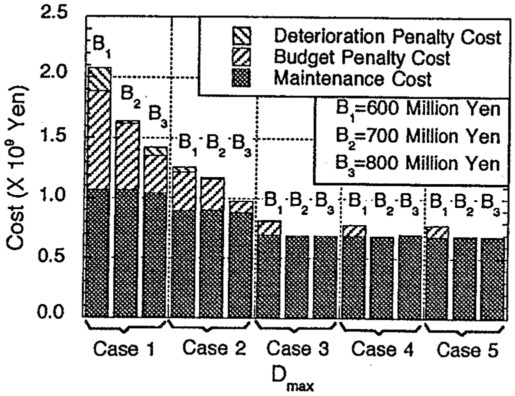


Fig. 5. Effect of Maximum Allowable Deterioration Degree

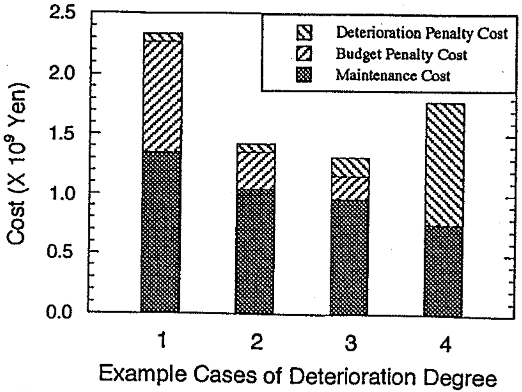


Fig. 6. Maintenance Cost and Range of Deterioration Degree

6. Conclusions

In this research, the application of *GAs* in the long-term maintenance strategy optimization of bridge decks has been examined. The following conclusions can be stated:

The coding method was effective in representing and processing the maintenance strategy optimization problem. All genetic operators were performed by means of two bits. The initial population was generated semi-randomly according to the deterioration degree of the previous year. In addition, multi-point crossover and mutation affected every bridge with the same probability and accelerated the optimization process.

From the sensitivity analysis, a moderate population size (50), a high crossover probability (80%), and a low mutation probability (0.1%) were found to be suitable values to satisfy the convergence requirement and calculation time of the optimization procedure. *GA* optimization could find the maximum allowable deterioration degree for a given maintenance budget. In addition, if this degree is given, the maintenance budget is the maintenance cost of the near-optimum maintenance strategy. On the other hand, by revising the range of the deterioration degree for each maintenance method, the decision maker could control the maintenance cost and the deterioration condition.

References

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