MAINTENANCE STRATEGY OPTIMIZATION OF BRIDGE DECKS USING GENETIC ALGORITHM

By Chunlu Liu,¹ Amin Hammad,² and Yoshito Itoh³

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ABSTRACT: With the rapidly increasing requirements of bridge maintenance and the limited budget available for this maintenance, the cost optimization of long-term maintenance strategy considering the network-level bridge system under an allowable deterioration level is becoming an important problem. However, the total maintenance cost is a function of the number of bridges and their deterioration degrees, the planning period, and the maintenance methods. The selection of the optimization algorithm is important to get the optimal solution of this problem. In this research, using the bridge deck as an example, the search procedure and optimization technique of the long-term maintenance cost of a network-level bridge system are presented using a genetic algorithm. A population of maintenance strategies evolves from one generation to the next generation by applying the principles of natural selection and survival of the fittest. The feasibility of this method is demonstrated using a real-world example, and the results are compared with the conventional maintenance planning. In addition, several maintenance policies are suggested and compared.

INTRODUCTION

Bridge maintenance strategy decision making has become a major problem for the highway agencies because of the rapidly increasing requirements of bridge maintenance. According to the White Paper on Construction (1994), the existing civil infrastructure in Japan, such as roads and bridges, built during the high economic growth period in the 1960s will need to be replaced by early next century. It is predicted that the maintenance cost of this civil infrastructure will increase to 50% of total public works investment by 2020. In 1990, this cost was 19% of total public works expenditures. Without corrective maintenance activities, bridge deterioration can lead to loading capacity reduction of the bridge, its closure, or in the worst case, catastrophic failure. The bridge deck is an important part of the bridge and it is directly subjected to cyclic loading and harsh environmental conditions. Furthermore, concrete decks are more widely used than steel decks and they need maintenance more frequently. However, since the specific inspection is usually done once every five years, and since the budget available for bridge maintenance is limited, there is a growing need for the optimization of long-term maintenance strategy considering the network-level bridge system in order to minimize the total maintenance cost. In this paper, a maintenance strategy is defined as a plan specifying the set of maintenance methods used for a bridge system during a specific planning period. Several studies have investigated the maintenance strategy optimization of bridge decks. Weyers et al. (1984) presented decision models based on cost-benefit analysis. Jacobs (1992) used the 0-1 integer mathematical model to optimize the schedule of long-term bridge deck rehabilitation and replacement. Markow (1994) suggested a life-cycle cost approach to decide the time and methods of improving bridge decks.

However, the selection of the optimum maintenance strategy is a challenging task because the number of possible combinations increases exponentially with the number of bridges N, the planning period, T, and the number of maintenance alternatives M. The number of all combinations of maintenance strategies is NMT. This selection will be more complicated if other conditions are considered such as the relationships among bridge elements and among different bridges, the limited resources, the requirement of the allowable deterioration limit, and so on. Practical real-world problems cannot be solved easily using conventional mathematical planning techniques because the solution time increases almost exponentially with the previous factors (Jacobs 1992).

Genetic algorithms (GAs) are optimization programs based on the mechanism of natural selection and natural genetics (Goldberg 1989). In GAs, natural selection is generally implemented through three genetic operators: selection, crossover, and mutation. A population of candidate strategies, usually coded as binary bit strings, is modified from one generation to the next by the probabilistic application of the genetic operators. GAs have been used in many domains of civil engineering such as road maintenance planning (Chen et al. 1994) and risk-based bridge management (Cesare et al. 1993). GAs are used in this research for the bridge maintenance strategy optimization for the following reasons: First, GAs do not work with the optimization parameters themselves, but with a discrete coding of the parameters set in the form of finite length strings that represent the artificial chromosomes. GAs process populations of these strings in successive generations. Furthermore, GAs only use the objective function information without the information of the derivatives or other auxiliary knowledge. In the case of the real-world bridge maintenance strategy optimization problem, it is difficult to obtain the derivatives of the objective function. Because the alternatives that can be selected as bridge maintenance strategy are determined and finite, the optimization of these alternatives is a discrete problem that can be solved by GAs. Second, GAs search from a number of points at a time, in contrast to the single-point approach of the traditional optimization methods such as the integer mathematical model. This means that GAs can process a large number of bridge maintenance strategies at the same time. Furthermore, GAs use probabilistic transition rules, not deterministic rules to guide the search towards regions of the search space with expected improvement. The operators including reproduction, crossover, and mutation improve the search process in an adaptive manner. These differ-

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ences contribute to the GAs' robustness in the long-term maintenance strategy optimization of a network-level bridge system, and result in many advantages compared with other optimization techniques. In this research, using the bridge deck as an example, the GAs optimization techniques for the maintenance strategies of a bridge system are developed, and the feasibility of this method is demonstrated using a numerical example.

**BRIDGE DECK MAINTENANCE STRATEGY**

Because of the rapid growth in the Japanese economy, there has been a sharp increase in the traffic load and traffic volume on the bridge decks. According to the newest version of the specification of Japan Road Association ("Specifications" 1994), the truck load and the minimum concrete deck thickness are 245 kN (25 tf) and 18 cm, respectively. However, a large number of the existing decks have been designed with smaller thicknesses according to previous specifications to support lower truck loads of 196 kN (20 tf). The minimum concrete deck thickness were 14, 16, 16, and 17 cm in the previous versions of 1964, 1973, 1980, and 1990. This problem has been magnified because of the large percentage of overloaded trucks. For these reasons, bridge deck maintenance has been given special importance in Japan.

Researchers and agencies have given different classifications and definitions to maintenance methods (Hanshin 1987; Harper 1991; Weyers et al. 1984). In this paper, the following definitions of four maintenance methods are adopted (Harper 1991). The first, routine maintenance, consists of the tasks that do not change the deck structure and do not improve the deck function such as timely cleaning and removing snow and ice. The second, repairs, are those activities that do not require relieving dead loads, and can be performed with only partial traffic closure. For instance, patching and sealing can only restore a good deck surface using flexible bituminous material or cement mortar. Repair prolongs the life of the bridge deck, but it may not prevent future deterioration. The third, rehabilitation, involves major repair requiring special efforts and sometimes closure of the bridge to traffic. Attaching additional longitudinal girders or steel plates, or increasing the cover thickness of the reinforcement is common rehabilitation method. For rehabilitation to be of benefit, the existing superstructure must be in fairly good condition. Rehabilitation can be a measure to allow time to develop plans for deck replacement or bridge replacement. Finally, the fourth, replacement is defined as a complete replacement of the bridge deck, and is generally performed by cast-in-place and prestressed concrete. Another approach often used in Japan is to replace the concrete deck by a steel one. Deck replacement also needs closure of the traffic. Its prerequisite is that superstructure and substructure systems can be expected to be in service as long as the new deck.

Bridge inspection is usually performed in two ways, routine inspection and specific inspection (Usage 1992). Routine inspection is undertaken every year to determine the condition of the bridge from which recommendations for specific inspection may be given if necessary. Specific inspection is made in order to collect more detailed information about some bridge decks that are structurally or functionally deficient. According to the results of inspection, the conditions of bridge decks are assessed to be one of five deterioration levels. At level I, deterioration is very serious and is affecting the serviceability and traffic safety, i.e., the bridge deck needs to be improved promptly by rehabilitation or replacement. At level II, deterioration is serious, and the function or structure is inadequate. Repair, rehabilitation, or replacement is necessary in order to restore the design traffic function or the design loading capacity. At level III, the bridge deck satisfies the functional and structural requirement, and replacement is not an economic method. However, deterioration is aggravating, and pursuit investigation is necessary. At level IV, deterioration exists, but is minor—routine maintenance and repair are two suggested maintenance alternatives. At level V, the bridge deck is like new, and routine maintenance is enough. As shown in Fig. 1, the deterioration levels V, IV, III, II, and I are quantified as deterioration degree ranges 0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and 0.8–1, respectively.

**DETERIORATION AND COST MODELS**

The damage causes and types of concrete bridge decks are of many kinds (Hanshin 1987). The major types of damages are cracking, exfoliation, water leakage, and partial dropping in the deck's tensile concrete. Another rare case is the breaking of reinforcing bars due to fatigue. The damages result from (1) overloading such as excessive axial loads and increasing truck load and traffic volume; (2) design problems such as insufficient deck thickness, insufficient distribution bars, and low quality of concrete; and (3) construction mistakes such as insufficient compaction during concrete placing.

Fig. 1 shows the conceptional graph of the deterioration process and the suggested maintenance methods corresponding to each deterioration level. The horizontal and vertical axes indicate time and deterioration degree (or deterioration level) of a bridge deck, respectively. With only routine maintenance, the bridge deck will deteriorate according to curve 1 in Fig. 1. When repair, rehabilitation, and replacement are made, deterioration will progress according to curves 2, 3, and 4, respectively. If a disaster such as an earthquake or an accident occurs, the deck deterioration degree will increase suddenly as shown in curve 5. A similar situation happens when a change of the specifications occurs, such as increasing the design truck load. In practice, bridge decks are not given the due repair and rehabilitation, and in most of the cases the bridge deck deteriorates until replacement is the only possible solution. In this case, the bridge deck will deteriorate over time from the initial construction condition following curve 1 until it reaches the allowable limit at the end of its functional life. The function of the bridge deck may be prolonged by maintenance actions. Otherwise, it will deteriorate until its structural failure level.

**Deterioration Model**

Many deterioration models were developed through analyses, tests, and statistics (Sobanjio 1993). Although some nonlinear mathematical models have been built to embody the
TABLE 1. Yearly Deterioration Rate R(A, Tr)

<table>
<thead>
<tr>
<th>Traffic coefficient</th>
<th>Bridge Age A (yr)</th>
<th>0 – 10</th>
<th>10 – 20</th>
<th>20 – 30</th>
<th>30 – 40</th>
<th>&gt;40</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T[1]</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
</tr>
<tr>
<td>≤1.0</td>
<td>0.000</td>
<td>0.025</td>
<td>0.030</td>
<td>0.035</td>
<td>0.035</td>
<td></td>
</tr>
<tr>
<td>1.0 – 1.1</td>
<td>0.025</td>
<td>0.030</td>
<td>0.035</td>
<td>0.035</td>
<td>0.040</td>
<td></td>
</tr>
<tr>
<td>1.1 – 1.2</td>
<td>0.030</td>
<td>0.035</td>
<td>0.040</td>
<td>0.045</td>
<td>0.050</td>
<td></td>
</tr>
<tr>
<td>&gt;1.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 2. Parameters of Maintenance Methods

<table>
<thead>
<tr>
<th>Maintenance method</th>
<th>Deterioration degree</th>
<th>Impact</th>
<th>Unit cost</th>
<th>GA code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routine maintenance</td>
<td>0.0 – 0.8</td>
<td>0.01</td>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>Repair</td>
<td>0.2 – 0.8</td>
<td>0.05</td>
<td>2,500</td>
<td>25</td>
</tr>
<tr>
<td>Rehabilitation</td>
<td>0.4 – 1.0</td>
<td>0.40</td>
<td>20,000</td>
<td>200</td>
</tr>
<tr>
<td>Replacement</td>
<td>0.6 – 1.0</td>
<td>0.90</td>
<td>40,000</td>
<td>400</td>
</tr>
</tbody>
</table>

Damage types and damage causes (Cady and Weyers 1984; Markow 1994), these models are difficult to be adopted in practical application at present due to the lack of many parameters' values. Therefore, in this research, a linear deterioration model considering the initial conditions, the yearly deterioration rates, and the impact of maintenance activity is adopted as shown by the following equation (Jacobs 1992):

\[
D(t) = D(0) + \sum_{j \in I(A)} \mu \times R(A, Tr) - \sum_{j \in I(A)} I_a(j)
\]  

where \(D(t)\) = deck deterioration degree of a bridge at the end of year \(t\), \(D(0)\) = the initial deterioration degree at the beginning of the maintenance planning period (year 0), which is found from the assessment results. For deterioration levels I, II, III, IV, and V, the values of \(D(0)\) are taken at the middle of the ranges shown in Fig 1 as 0.9, 0.7, 0.5, 0.3, and 0.1, respectively. \(R(A, Tr)\) is the yearly deterioration rate of a concrete bridge deck at year \(j\). A fixed yearly average rate was used for all bridges in previous research (Jacobs 1992). However, the yearly deterioration rate depends on the bridge age \(A_j\) and the traffic coefficient \(Tr\). Here, \(A_j\) is the time from the construction or replacement year to the maintenance year. It is adopted that rehabilitation will prolong the deck age by 10 years (Silano 1993). \(Tr\) is the average of the ratio between the predicted maximum traffic volume \(V_{max}\) and the design traffic volume \(V_d\). The ratio between the maximum truck load \(F_{max}\) and the design truck load \(F_d\) is \(V_{max}(j)/V_d + F_{max}(j)/F_d\). Table 1 shows the relationship between the yearly deterioration rate \(R(A, Tr)\), and the bridge age \(A_j\) and the traffic coefficient \(Tr\). The deterioration rate is determined according to the following three principles (Cady and Weyers 1984): (1) deterioration can be expected to begin after 10 years of the bridge construction or replacement; (2) concrete decks deteriorate at about 2% per year after deterioration has been initiated; and (3) deterioration speeds up with the increase in the bridge age and the traffic coefficient. In addition, the yearly deterioration rate is affected by many other factors, such as the thickness of the deck, the construction quality, the previous maintenance activities, the environmental conditions, and so on. However, for the sake of simplicity, these factors are not considered in the present study. The factor \(\mu\) reflects the deterioration property of material. In this paper, 1.0 and 1.1 are applied for concrete and steel decks, respectively. \(I_a(j)\) is the impact on the deck deterioration degree due to the maintenance activity \(m\) at year \(j\). Table 2 shows the parameters of the maintenance methods. The following assumptions are adopted for the impact values of the maintenance methods as shown in column 3 of Table 2. First, routine maintenance does not reduce the deterioration degree, and its impact is 0.01. Second, repair only releases the deterioration of the corresponding year, and its impact is 0.05. This value is equal to the maximum yearly deterioration rate. Third, rehabilitation decreases the deterioration by two levels, and its value is 0.4. Finally, replacement can restore the bridge deck to the initial construction condition, and its impact is 0.9.

The applicability of the maintenance methods is specified in this research for each deterioration level as shown in column 2 of Table 2. Routine maintenance is suitable for deterioration levels II, III, IV and V (\(D = 0 \sim 0.8\)); repair is suitable for deterioration levels II, III, and IV (\(D = 0.2 \sim 0.8\)); rehabilitation is suitable for deterioration levels I, II, and III (\(D = 0.4 \sim 1.0\)); and replacement is suitable for deterioration levels I and II (\(D = 0.6 \sim 1.0\)). The maintenance method at any year will be selected from the suitable methods semirandomly considering the maximum allowable deterioration degree. This quasi-stochastic approach was found more suitable for this problem than other stochastic and fuzzy approaches. If the deterioration degree \(D(t)\) is less than the yearly deterioration rate \(R(A, Tr)\) at year \(t\) due to the impact of the maintenance activity, the yearly deterioration rate is used as the deterioration degree. This is because the maintenance activity is assumed to take place at the beginning of the year. In addition, it is assumed that only one of these four maintenance methods is carried out, and rehabilitation or replacement will take place at most once in 5 yr to save the cost of man power and maintenance equipment.

**Maintenance Cost**

In spite of the close relationship between bridge inspection cost and maintenance cost, these costs are assumed to be covered by different budgets. The yearly deck maintenance cost of a bridge is calculated using the bridge deck area and the unit cost of the selected maintenance method. The maintenance cost \(C\) of a bridge system over the maintenance planning period is determined by

\[
C = \sum_{i} \sum_{t} [(1 + r)^{-1} \times c_m(i, t) \times L(i) \times W(i)]
\]

where \(N\) = the number of bridges, \(T\) = length of the planning period; \(r\) = discount rate that is assumed to be constant during the planning period; \(c_m(i, t)\) = unit cost of maintenance method \(m\) that is used for bridge \(i\) at year \(t\). Estimating the \(c_m(i, t)\) is difficult because it needs detailed data about the man power, the equipment, and the material necessary for each method (Bieniek et al. 1990). In this paper, the unit costs are average values based on engineering experience only as given in columns 4 and 5 of Table 2 in Japanese Yen and U.S. dollars, respectively. \(L(i)\) and \(W(i)\) indicate the length and width of bridge \(i\), respectively. The maintenance cost is calculated at the beginning of the planning period without considering the possible changes in unit costs due to inflation.

**Objective Function**

In engineering optimization problems, the objective function usually represents the relationship between the cost and the benefit of an operation as a value that should be minimized or maximized. The benefit of a maintenance strategy can be measured by the expected improvement in the deterioration degree of the bridge decks. In this paper, the deterioration degree is kept less than the maximum allowable deterioration degree by choosing an appropriate maintenance strategy. It is noticed that the maximum allowable deterioration degree is a function of
the bridge age, the bridge class, the maintenance budget, and so on. For instance, old bridges that will be replaced soon should be given a higher value. In this paper, the maximum allowable deterioration degree of a bridge deck is given only according to its age, and abbreviated as $D_{max}(A_i)$. Table 3 shows several possible cases of $D_{max}(A_i)$ for every age range. The constraint on $D_{max}(A_i)$ is considered in the objective function as a penalty cost. The cost of a maintenance strategy, in which the deterioration degree of a bridge deck at year $t$ is higher than $D_{max}(A_i)$, will be penalized by an additional penalty cost. The more severely a strategy does not follow the preceding constraint, the higher it is penalized. The penalty cost is zero if the constraint is satisfied. The objective function $Z$ is the sum of maintenance cost and penalty cost as shown in the following equation:

$$Z = C \times \left(1 + p \times \sum_{i=1}^{N} \sum_{t=t}^{T} \frac{D(i,t) - D_{max}(A_i)}{D_{max}(A_i)}\right)$$

(3)

where $D(i,t) = \text{deterioration degree of bridge } i \text{ at year } t$. The penalty cost for the deterioration rate may be adjusted by an importance weight $p$. However, the value $p=1$ is used in this paper. It is found that the convergence works well for a small generation number in the numerical example. The maintenance budget is considered as a constraint in the selection operator of GA as will be explained in the next section. In addition, the following constraints are taken into account in the optimization procedure.

If the superstructure or substructure members are severely deteriorated and will be replaced soon, the deck rehabilitation or replacement will not be economically justifiable because the new deck will be used only for a short period. Considering this problem, a constraint is applied according to the assessment result of the whole bridge at the beginning of the planning period. 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 until the whole bridge is rehabilitated or replaced.

Some bridges have a special relationship such as being on the same roadway, or over the same river. To maintain the traffic service of a bridge network during rehabilitation or replacement, a constraint that bridges with a special relationship should not be improved simultaneously is required. One approach to this problem is to consider the benefit resulting from the maintenance strategies on the traffic conditions of the road network. However, considering this benefit within the same objective function would make the problem much more complicated. This problem can be solved by first choosing several maintenance strategies that are near-optimum GA solutions from the cost point of view, and then comparing these strategies from the traffic point of view. This paper targets the first step of finding the minimum cost maintenance strategy. The effect on the traffic conditions of the road network is only visually checked using a geographic information system (GIS) as will be explained later.

**MAINTENANCE STRATEGY OPTIMIZATION USING GA**

The flowchart illustrating the GA implemented in the present study is shown in Fig. 2. The three modules numbered in this figure are the main processes of the GA. These are the production of the initial generation; the reproduction by selection, crossover, and mutation operators; and the decoding and evaluation. These modules are explained in the following sections. The GA starts from the parameter definition, and the coding structure is determined at the same time. The initial population of the maintenance strategy will be generated according to the deterioration degree. For each generation, the GA first generates strings by selecting two parents from the

![Flowchart of Maintenance Strategy Optimization Using GA](attachment:flowchart.png)

previous generation and reproducing them by crossover and mutation until the whole population is created. Then, the GA will decode and evaluate the strings of this generation. The objective function including maintenance cost and penalty cost is calculated by decoding every string. This procedure will repeat many times until the near-optimum maintenance strategy is found.

**Code Design and Population Production of Initial Generation**

An essential characteristic of GAs is the coding of the variables that describe the problem. The most common coding
method is to transform the variables into a binary string of a specific length. In this research, a new approach to coding is implemented.

As mentioned before, four kinds of maintenance methods are available, so that the maintenance method of each bridge at any year must be represented by two binary values. This couple of bits is called here basic string unit. The meaning of the codes is shown in column 6 of Table 2. To represent the maintenance methods of a network-level bridge system over the planning period T, the coded structure is designed as shown in Fig. 3. The final string consists of many substrings representing all bridges in a given order, and the string length is the sum of all substrings' lengths. Every substring represents the maintenance strategy of a bridge in a bridge system. In a substring, every basic string unit from left to right represents the maintenance method at one year from the beginning to the end of the planning period. This structure has three levels representing the bridges, the maintenance methods for every year, and the string bits, respectively.

Another feature of this coding is its sequence dependency that represents the effects of the maintenance activities in previous years on the maintenance decision making of the following years. In the conventional coding of GAs, there is no such relationship among the different bits, and the string population of the initial generation is produced bit by bit randomly. In this research, every basic string unit of a substring depends on the bits of the previous years and partially decides the values of the bits of the following years. This feature is reflected in the whole process of the implemented GA. The two codes of every basic string unit are generated simultaneously. Furthermore, these two binary values are selected semirandomly from the acceptable maintenance methods as shown in Fig. 1 considering the deterioration degree at the previous year. The substrings of bridges are generated one by one and compiled to the whole string of the bridge system. This procedure is repeated until enough strings are generated to make the population pool.

**GA Operators: Selection, Crossover, and Mutation**

In the present research, selection is done on the basis of relative objective function and maintenance cost of each individual maintenance strategy in one generation. The maintenance strategies that satisfy the following conditions are selected to be the parents of the new maintenance strategies in the next generation: (1) the objective function values are equal to or less than the average objective function value of the population; and (2) the maintenance costs are equal to or less than the maintenance budget. The first condition is a fundamental condition that all selected maintenance strategies must satisfy. The second condition is neglected if the maintenance costs of all maintenance strategies are greater than the maintenance budget within one generation, which may happen at the first several generations.

In the reproduction procedure of new generations, the operators of crossover and mutation are performed. Because the basic string unit is of two bits, the crossover points should be between the basic string units. Furthermore, multipoint crossover is introduced within every substring so that the number of the crossover points is same as the number of bridges. The multipoint crossover operator is shown in Fig. 4. Once the crossover points are randomly selected, the parts to the left of the crossover point in the substrings will be retained and the parts to the right of the crossover point will be exchanged. To ensure that the new strings express feasible maintenance strategies, the substrings to the right of the crossover point will be verified and regenerated if necessary using the same method as stated in the previous section.

Similarly, with a probability of mutation, one basic string unit is altered into another within every substring. After the mutation position is randomly selected, the substrings to the left of the mutation position will be retained as a part of the new substring, the two bits at the mutation position are mutated with the feasible values according to the deterioration degree of the previous year, and the substrings to the right of the mutation position will be verified using the same method as stated for the crossover operator.

**Decoding and Evaluation**

The decoding process of a string is inverse to the generation process. 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 area of every maintenance method at every year are found, and maintenance costs and penalty costs are calculated. After many generations, the best member of the population with a minimum value of the objective function will represent a near-optimum solution of the problem.

One or more of the following conditions are used as the terminating conditions: (1) the convergence condition of the minimum value of the objective function (1% among 20 successive generations); (2) the difference between the average and the minimum of the objective function values among a population (1% among 20 successive generations); and (3) the maximum generation number.

**NUMERICAL EXAMPLE**

Using the bridge data of Nagoya city (the third largest city in Japan), the second and third writers are engaged in another research about developing a bridge-object-oriented database management system integrating GIS technology (Hammad 1995). To examine the approach analyzed in this paper, the data of 287 bridges (269 with concrete decks, and 18 with steel decks) are obtained from this database. Fig. 5(a) shows the ranges of the construction years of these bridges. The initial deterioration levels of these bridges are assessed in II, III, IV, and V. Fig. 5(b) shows the percentage of bridges for each deterioration level. The traffic coefficients Fr of these bridges are between 1.0 and 1.1. Their widths and lengths are from 2.2–49.2 m, and from 15.1–531.8 m, respectively. The period of maintenance planning is taken as 5 yr in accordance with the maintenance planning of other civil infrastructures in Japan. The deck maintenance budget and the maximum allowable deterioration degree are assumed to be 8,000,000 (800,000,000 yen) and 0.8 (case 5 in Table 3), respectively. The discount rate is assumed 1.75% per year during the planning period. The unit costs of maintenance methods are assumed constants and have linear relationships with the impacts of maintenance methods as shown in column 4 of Table 2. According to the GA optimization mechanism introduced before, with a population size of 50 and a crossover probability
of 80%, after 100 generations, 4,000 maintenance strategies (100 x 50 x 80%) are generated and evaluated. The analysis procedure has been programmed in FORTRAN. The execution time per run on a SUN SPARC Station II is about 6 h.

**Parametric Study**

A sensitivity analysis is done to check the effects of the population size $Pop_s$ (10, 20, 30, 40, 50, and 60), the crossover probability $P_c$ (0, 20, 50, 60, 70, 80, 90, and 100%), and the mutation probability $P_m$ (0, 0.01, 0.05, 0.1, 0.5, 1, 5, and 10%). The minimum values of the objective functions of some runs are shown in Figs. 6(a, b, c), respectively. For the comparison purpose, only the maximum generation number of 100 is used as the terminating condition. It is found that convergence will improve and calculation speed will decrease with bigger population size, bigger crossover probability, and smaller mutation probability. Fig. 6(a) shows that the population size affects the near-optimum results. However, for $Pop_s = 40, 50$ and 60 the minimum values of the objective function almost converge to a fixed value when $P_c = 80\%$ and $P_m = 0.1\%$. The value of $Pop_s = 50$ gives better results than other $Pop_s$ values. Similarly, Fig. 6(b) shows that the convergence speed is slow when the crossover probability is 20%, and the results are similar for $P_c = 60, 80$, and 90% when $Pop_s = 50$ and $P_m = 0.1\%$. Fig. 6(c) shows that, taking $Pop_s = 50$ and $P_c = 80\%$, if the mutation probability $P_m$ is high such as 5%, the minimum objective function values fluctuate randomly and may even increase at certain generations because too many bits are mutated. However, when the generation number is changed to 200, this seeming increase tendency in the value of objective function for $P_m = 5\%$ is found to be temporary, and this value continues to fluctuate around an average value of about $9,000,000$ (900,000,000 yen). On the contrary, the convergence does not approach a good value for a too low $P_m$ such as 0.01%. Hence, a moderate population size (50), a high crossover probability (80%), and a low mutation probability (0.1%) are good for the GA performance considering the convergence requirement and calculation time. These values will be used in the following calculations.
For example, if the maximum allowable deterioration degree is given as case 3, the maintenance cost of $7,530,000 (753,000,000 yen) can be suggested as the maintenance budget. If the maintenance budget is inadequate such as $6,500,000 (650,000,000 yen), no maintenance strategy can satisfy the parameters of maintenance methods shown in Table 2. One solution to this problem is to reduce the unit costs or increase the impacts of the maintenance methods by developing new maintenance techniques. Another solution is to reduce the number of the bridges by purposefully neglecting the maintenance of less important bridges for a certain period. Fig. 8 shows the location of the bridges for each maintenance method at the second year from the previous solution of case 3 using the previously mentioned geographic-information-system-based bridge management system. The number of bridges with routine maintenance, repair, rehabilitation, and replacement are 173, 85, 27, and 2, respectively. City traffic planners can use this system for visually checking the effects of the GA near-optimum strategy on the traffic flow. If the maintenance strategy is found inefficient from the traffic point of view, other near-optimum strategies can be chosen from the GA population for further comparison.

Case Study

In this case study, several maintenance policies are compared considering the effect of the planning period. The planning period \( T \) is an important parameter that depends on the general economic policy of the country, and on the credibility of the information used for planning. The value of \( T = 5 \) yr has been adopted in the previous calculations. However, to have a meaningful and rational comparison among different maintenance policies, this comparison should be ideally done for the total economic life of the bridge. The economic life span of a bridge is the period for which the bridge fulfills its functions economically, and is less than the structural life of
the bridge. As the average economic life span of bridges in Japan is estimated to be 50 yr (Nishikawa 1994) and the actual average age of the bridges of Nagoya city is about 25 yr, the maintenance planning of the coming 25 yr is carried out in this paper. To check the effect of the planning period on the GA optimization results, two maintenance policies are investigated. The first policy is for $T = 25$ yr, and the second is for $T = 5$ yr. In the second policy, maintenance strategies for five sequential planning periods are found. The deterioration degree at the end of the previous planning period is used as the initial deterioration degree for the next planning period. As analyzed before, routine maintenance is usually the only maintenance method used until the bridge deck deteriorates very seriously. This approach will be called the conventional maintenance strategy. In this paper, the deterioration degree and the maintenance cost, when the conventional maintenance strategy is followed, are calculated according to Eqs. (1) and (2), respectively. However, only routine maintenance or replacement is applied, depending on whether the deterioration degree is less or greater than $D_{\text{max}}(A_i)$, respectively. The conventional maintenance planning is taken as the third maintenance policy for the coming 25 yr. Applying these three policies, the maintenance planning of the 287 bridges of Nagoya City is made using case 5 of $D_{\text{max}}(A_i)$. The discount rate is fixed and the inflation effect on the unit costs is not considered.

Fig. 9 shows an example of the change in the deterioration degree of the bridge deck for the three maintenance policies. The bridge is relatively new (constructed in 1983), and its initial deterioration degree is $D(0) = 0.1$. The dots in Fig. 9 show the maintenance methods at every year. It can be noticed that the inclinations of the lines increase at the ages of 10, 20, 30, and 40 yr because of the increase of the yearly deterioration rate with the age of the bridge. It can also be noticed that the deterioration degree at the end of the total planning period in the case of the first policy (GA optimization strategy, $T = 25$ yr) is higher than those of the other two policies. This is a normal result of this policy which tends to emphasize the economic life span of the bridges. Figs. 10(a, b, c) show the deck areas of each maintenance method for the first, second, and third policies, respectively. Because the values of the replaced and rehabilitated areas are small compared with those of the routine maintenance and the repaired areas, the former values are scaled up five times. In Fig. 10(a), because the planning period is long, there is a small replaced area, and the ratios among the areas of the other maintenance methods are steady throughout the planning period. In Fig. 10(b), because the planning period is 5 yr, the replaced, rehabilitated, and replaced areas are very large, and the routine maintenance area.
is small in the first year of every planning period. This can be explained by the fact that the deck deterioration degree in this policy approaches \(D_{\text{max}}(A)\) at the end of every planning period. The replaced area in the third policy is much larger than those of the first and second policies. It can be noticed also that the replaced area in Fig. 10(c) tends to increase with the passage of time.

Figs. 11(a, b) show the maintenance costs and the average deterioration degrees, respectively. The average deterioration degree is calculated for the unit area of the deck of all bridges. The total maintenance costs of the coming 25 yr for the first, second, and third policies are \$47,040,000, \$54,330,000, and \$75,080,000 (4.7 billion, 5.4 billion, and 7.5 billion yen), respectively. Because the planning period in the second policy is 5 yr, the cost at the first year of every planning period is very high. Furthermore, for the third policy, the maintenance cost fluctuates as shown in Fig. 11(a). This means that the second and third policies are difficult to implement and the traffic conditions will be affected by the large number of bridges to be replaced or rehabilitated in one year. The first policy, on the contrary, needs lower budget (87 and 63%, of the budgets of the second and third policies, respectively), and gives a stable cost per year of about \$2,000,000 (200,000,000 yen). Fig. 11(b) shows the average deterioration degrees of the first and second policies increase gradually toward the maximum allowable deterioration degree at the end of the planning period. The average deterioration degree of the third policy is more steady. However, its cost is prohibitive and the resulting strategy is far from rational.

From the previous results, it can be noticed that the maintenance cost can be roughly estimated according to several factors. These factors include: (1) the economic life span of the bridge \(S\); (2) the planning period \(T\); (3) the yearly deterioration rate \(R\) and the maximum allowable deterioration degree \(D_{\text{max}}\); (4) the unit costs \(c\), and impacts \(I\), of the maintenance methods; and (5) the discount rate \(r\). The average maintenance cost of the deck unit area per year \(c'\) can be written as a function of the previous parameters

\[
c' = f(S, T, R, D_{\text{max}}, c, I, r)
\]

A simple linear function can be presented considering a fixed discount rate as follows:

\[
c' = \alpha \times \frac{S}{T} \times \frac{R}{D_{\text{max}}} \times \sum_{i=1}^{L} \frac{c_i}{I_i}
\]

The value of \(\alpha\) can be found from the GA optimization results. For \(S = 50\) yr, \(T = 25\) yr (first policy); \(R = 0.030, D_{\text{max}} = 0.7\), and considering the total cost for 25 yr as \$47,040,000 (47 billion yen), the value of \(\alpha\) can be found from (5) to be 0.638. Similarly, for \(T = 5\) yr (second policy), it can be found that \(\alpha = 0.0147\). The average value of these two values is \(\alpha = 0.0392\). An example of how to use this equation is to find the average cost per unit area per year for \(T = 10\) yr. This value is found to be about \$133 (m²/yr) (1,300 yen/m²/yr).

The previous equation can help in roughly estimating the influence of the key parameters on future maintenance policies.

**SUMMARY AND CONCLUSIONS**

In this research, the application of GAs in the long-term maintenance strategy optimization of bridge decks was examined. A GA including reproduction, crossover, and mutation was used to find the near-optimization long-term maintenance planning for a network-level bridge system. A practical numerical example was performed. The maintenance strategies, the deterioration degrees, and the costs were evaluated. The following conclusions can be stated:

Unlike traditional GAs, every two bits of the strings is a basic string unit that represents a certain maintenance method of a bridge deck at one year. This coding method was effective in representing and processing the maintenance strategy optimization problem. All genetic operators such as reproduction, crossover, and mutation were performed by means of two bits. The initial population was not generated completely at random, but semirandomly by selecting from the feasible maintenance methods using the deterioration degree of the previous year. The substrings to the right of crossover points or mutation points were verified and regenerated after the crossover or mutation operator when necessary. In addition, multipoint 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 can find the maximum allowable deterioration degree for a given maintenance budget.

On the other hand, if the maximum allowable deterioration degree is given, the maintenance budget is the maintenance cost of the near-optimization maintenance strategy.

It was demonstrated that GA can deal with the long-term maintenance planning of a network-level bridge system. By a comparison with the conventional maintenance strategy, GA could find life-cycle near-optimimum maintenance budget of a bridge system. In addition, a simple formula was suggested to
estimate the average cost per unit area per year considering the key parameters of the maintenance planning policy.

APPENDIX. REFERENCES


