Optimal Maintenance Planning of Network-Level Bridges

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1. Introduction

In this research, the initial condition of a bridge is assessed on the basis of bridge inspection database. The future conditions of bridges are predicted using Markov Decision Process incorporating the effects of maintenance actions that will be adopted within the planning period. It is assumed that increasing the life of the bridge by good maintenance planning will decrease the average cost and environmental impact per year of the life cycle including construction and demolition stages. The objective functions, cost and environmental impact, are effected by the maintenance actions directly, and the increase of service life due to the maintenance actions indirectly. A Genetic Algorithm is implemented as a multi-objective optimization technique to set up and revise the Pareto optimal set of maintenance plans.

2. Prediction of Bridge Condition and Service Life

Taking the impacts of maintenance actions into account, the condition distribution P_i of a bridge component at year i is predicted through a nonstationary Markov chain model as follows:

$$P_i = P_0 \times \prod_{k=1}^{i} (Q \times M_{k,m}) \tag{1}$$

where, P_0, Q, and $M_{k,m}$ are the condition distribution at the inspection year, the condition transition matrix and the impact matrix of maintenance action m at year k, respectively. The service life of a bridge is the sum of the present age (l_p) and the predicted remaining life. The remaining life of a bridge is the number of years from the inspection year to the year when the bridge condition ($P_{l_{r,m}}$) reaches a given limit. The remaining life of a bridge ($l_{r,m}$) is determined according to Eq. (2) in the case we apply some maintenance actions in the planning period. To emphasize the effects of maintenance actions within the present planning period, it is assumed there are no maintenance actions after this period. A special case of $l_{r,m}$ is the remaining life (l_r) when we do not apply any maintenance action in the planning period.

$$P_{l_{r,m}} = P_0 \times \prod_{k=1}^{5} (Q \times M_{k,m}) \times Q^{l_{r,m}-5} \tag{2}$$

3. Objective Functions

The first objective function is the cost C of a bridge system over the maintenance planning period. C takes into consideration the cost of maintenance actions, C_m, and the reduction of construction and demolition costs due to the increase of service life, C_l ($C = C_m - C_l$). C_m is calculated as follows:

$$C_m = \sum_{i=1}^{N} \sum_{t=1}^{T} (1+r)^{-t} \times (a_d(i) \times c_{m,d}(i,t) + a_g(i) \times c_{m,g}(i,t) + l_e(i) \times c_{m,e}(i,t)) \tag{3}$$

where N is the number of bridges; T is the length of the planning period; r represents the discount rate that is assumed to be constant during the planning period; the symbols $a_d(i)$, $a_g(i)$, and $l_e(i)$ indicate the area of deck, the surface area of girder, and the length of expansion joint of bridge i, respectively. $c_{m,d}(i,t)$, $c_{m,g}(i,t)$, and $c_{m,e}(i,t)$ are the unit costs of deck, girder, and expansion joint of maintenance method m that is used for bridge i at year t. C_l is calculated as follows:

$$C_l = \sum_{i=1}^{N} a_d(i) \times \left(\frac{(1+r)^{l_p} \times c_c(i) + (1+r)^{-l_r} \times c_d(i)}{l_p + l_r} - \frac{(1+r)^{l_p} \times c_c(i) + (1+r)^{-l_{r,m}} \times c_d(i)}{l_p + l_{r,m}}\right) \times T \tag{4}$$

where, $c_c(i)$ and $c_d(i)$ are the unit area costs of construction and demolition actions of the whole bridge distributed on the bridge deck area, respectively. The unit area costs are estimated according to the design manuals such as *Planning Manual of Steel Bridge*(1985).

A similar approach is applied for calculating the environmental impact of CO_2 emissions. The direct and indirect environmental impacts E_m and E_l are calculated as shown in Eqs. (5) and (6), respectively.

$$E_m = \sum_{i=1}^{N} \sum_{t=1}^{T} (a_d(i) \times e_{m,d}(i,t) + a_g(i) \times e_{m,g}(i,t) + l_e(i) \times e_{m,e}(i,t)) \tag{5}$$

$$E_l = \sum_{i=1}^{N} a_d(i) \times (e_c(i) + e_d(i)) \times (\frac{1}{l_p + l_r} - \frac{1}{l_p + l_{r,m}}) \times T \tag{6}$$

where, $e_{m,d}(i,t)$, $e_{m,g}(i,t)$, and $e_{m,e}(i,t)$ are the CO_2 emissions per unit area of deck, girder, and expansion joint of maintenance action m used for bridge i. The symbols $e_c(i)$ and $e_d(i)$ are the CO_2 emissions per unit area of construction and demolition actions of the whole bridge, respectively. At this stage, the CO_2 emissions per unit area are determined following a linear relationship with the unit area cost.

4. Multi-objective Optimization Using Genetic Algorithm

Because Genetic Algorithm (GA) works with a population of points (Liu et al. 1995), it can capture many solutions simultaneously and can easily incorporate the concept of Pareto set in their selection operator. For each generation, the objective functions' values of all strings are compared, and the nondominated strings may revise the Pareto set of the previous generation.

To examine this approach, the data of 287 bridges in Nagoya city are obtained from the bridge inspection database. Fig. 1 shows that the average values of both cost and CO_2 emissions over each population go down with the increase of generation number. This result is corresponding to the optimization procedure that aims to minimize the cost and environmental impact at the same time. By sorting all non-dominated individuals generated over each generation, a Pareto set represents the best maintenance strategies in the current generation. Fig. 2 shows how the Pareto sets evolve to the left and down with the increase of generation number. The Pareto set of generation 100 shows the trade-off between the cost and the environmental impact. The decision maker can select one maintenance plan from this set according to his particular requirements.

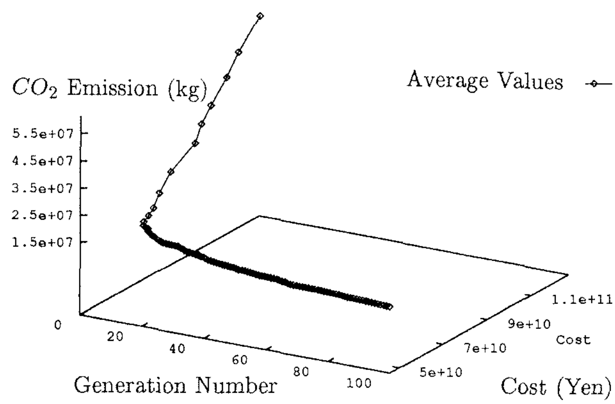

FIG. 1. Averages of Objective Functions

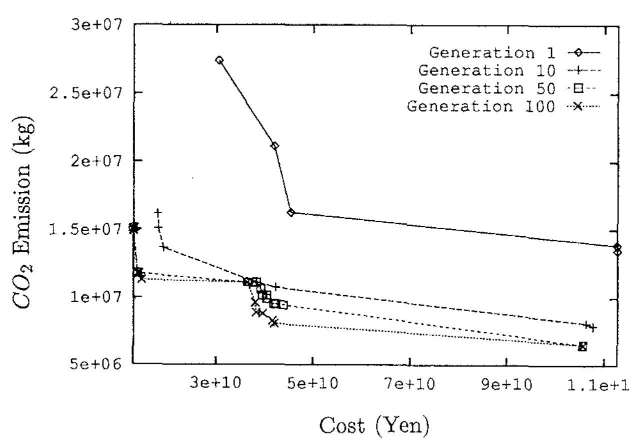

FIG. 2. Pareto Optimal Sets for Several Generations

5. Conclusions

(1) The future conditions and service lives of bridges were predicted using Markov decision process incorporating the effects of Maintenance actions.

(2) GA was successful in searching the near Pareto optimal set of a multi-objective optimization problem.

References

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[2] *Planning Manual of Steel Bridge.* (1985). Japan Steel Structure Association, Tokyo, Japan (in Japanese).