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Optimum maintenance scenario generation for existing steel-girder bridges based on lifetime performance and cost

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Abstract. This paper proposes a practical and realistic method to establish an optimal lifetime maintenance strategy for deteriorating bridges by considering the life-cycle performance as well as the life-cycle cost. The proposed method offers a set of optimal tradeoff maintenance scenarios among other conflicting objectives, such as minimizing cost and maximizing performance. A genetic algorithm is used to generate a set of maintenance scenarios that is a multi-objective combinatorial optimization problem related to the lifetime performance and the life-cycle cost as separate objective functions. A computer program, which generates optimal maintenance scenarios, was developed based on the proposed method using the life-cycle costs and the performance of bridges. The subordinate relation between bridge members has been considered to decide optimal maintenance sequence and a corresponding algorithm has been implemented into the program. The developed program has been used to present a procedure for finding an optimal maintenance scenario for steel-girder bridges on the Korean National Road. Through this bridge maintenance scenario analysis, it is expected that the developed method and program can be effectively used to allow bridge managers an optimal maintenance strategy satisfying various constraints and requirements.

Keywords: bridge maintenance; optimum maintenance scenario; life-cycle performance; life-cycle cost; steel-girder bridges.

1. Introduction

Within Korea, and other advanced countries, the current trend in the construction industry has focused on the maintenance of existing structures in lieu of new construction; consequently, the budget

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required for maintenance has increased. With the concept of the asset management and/or the life-cycle cost (LCC), bridge engineers have developed some of the most diverse analysis techniques, methodologies and systems in the world (Thompson, *et al.* 1998, KICT 1999, Miyamoto, *et al*. 2000). These methods basically aim to improve the efficiency of both the performance and cost of bridges through preventive maintenance. From the viewpoint of preventive maintenance, a prediction of the bridge's performance and an estimation of the cost should be required to make bridge maintenance cost-effective. However, most studies only focus on the theoretical point and do not consider the practical application (Furuta, *et al*. 2004, Liu and Frangopol 2005, Miyamoto, *et al*. 2000). Therefore, a systematic and integrated framework for bridge maintenance should be developed in order to make a practical application of LCC technique. The general model for the optimal maintenance of a LCC efficient bridge should consider the performance, which includes its condition and safety as well as the LCC of bridges. The maintenance method should follow the current development of the design concept and the maintenance technology and should overcome the limits of existing bridge maintenance systems. It is also necessary to develop a practical system for rational and economical bridge maintenance on the basis of its lifetime performance and the LCC.

This paper proposes a new method and a general model for LCC-effective optimal maintenance of bridges with an emphasis on considering the multiple, and often conflicting, objectives such as condition, safety, and cost. Next, the framework of the developed optimal maintenance program for the next-generation is presented. Finally, using the developed program, a process of generating an optimal maintenance scenario for a steel-girder bridge within the Korean National Road is presented.

2. New bridge maintenance method

The main purpose of bridge management is to establish a maintenance strategy that determines the time and method for repair, retrofit and replacement satisfying the minimum LCC and the minimum safety requirements. To satisfy this requirement, it is necessary to generate an optimal maintenance scenario among conflicting objectives, life-cycle performance and cost. Fig. 1 shows a graphical bridge management model that considers both the lifetime performance and the LCC. This paper suggests an actual method to evaluate, predict and estimate the life-cycle performance and the LCC and to generate an optimal maintenance scenario in order to apply the proposed model to bridge maintenance in a practical way. This paper briefly describes the main factors for establishing the optimal maintenance strategy mentioned above.

2.1. Life-cycle performance evaluation

Two considerations must be made to conduct an appropriate life-cycle analysis. First, a reasonable performance index must be established in order to evaluate bridge performance. Second, it is necessary to select a performance evaluation model and a quantitative analysis model of the repair/retrofit effects appropriate for the life-cycle analysis. Hence, to develop a performance evaluation model the multi performance index ("performance index" refers to the reliability index in this paper) and condition index are introduced. These two performance indexes can be integrated into a system level through the system reliability and bridge safety guidelines (MOCT/KISTEC 2003).

A time-variant reliability analysis is performed to evaluate the performance index and the effects of repair/replacement are quantified by using a response surface method (RSM) which is one of the

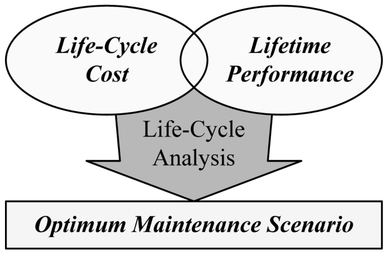


Fig. 1 Optimal maintenance concept considering lifetime performance and LCC

statistical safety evaluation methods. RSM is applied to quantify the deterioration model and the repair/retrofit effects in classified bridge types through the statistical analysis of existing bridges on the National Road (Park, *et al*. 2006). The condition index used in this study generalizes the discontinuous condition states based on the visual inspection applied to current bridge maintenance regulation (MOCT/KISTEC 2003). The information required for a performance evaluation using a condition index is obtained from the statistical analysis using existing data or the professional research data (KICT 2006). A profile for life-cycle performance and cost is executed by using a MLTR (Kong and Frangopol, 2001) program that can generate a life-cycle profile that considers the effect of maintenance interventions. The performance index profile of a deteriorating bridge can be evaluated by superposing the initial performance index profile and additional performance index profiles associated with all subsequent maintenance interventions as follows:

$$P(t) = P_0(t) + \sum_{t=1}^{n} \Delta P_i(t) \tag{1}$$

where $P(t)$ = initial performance profile function, P_0 = initial performance index, n = number of maintenance interventions applied in bridge lifetime, t = time (year), $\Delta P_i(t)$ = change of performance profile with the maintenance intervention i.

2.2. Life-cycle cost estimation

In addition to the direct cost paid by the bridge agency, indirect costs such as user cost and failure cost are important considerations for the life-cycle analysis. The present value of the expected total cumulative cost (maintenance and failure) related to the bridge with n failure modes can be formulated as follows (Kong and Frangopol 2005):

$$C_t^P(t_h) = \sum_{j=1}^{n} \{C_{M,j}^P(t_h) + C_{F,j}^P(t_h)\} \tag{2}$$

where $C_{M,j}^P$ and $C_{F,j}^P$ = the present value of the expected total cumulative maintenance cost and the failure cost related to the failure mode j, respectively; n = number of failure modes; t_h = time period considered. The expected value of the total cumulative maintenance cost is obtained from the sum of all expenditures by the applied maintenance interventions for each failure mode until a considered time horizon.

In considering the failure cost, it is necessary to have a process that gives the failure probability that should be estimated from the limit states of the structure. Unfortunately, the probability of failure cannot be easily calculated. For this reason, many of the existing LCC analysis systems at the maintenance stage use the cost estimation without considering the failure probability. This study tries to evaluate the failure cost as a function of reliability reduction over time for the optimal maintenance. The expected value of the total cumulative failure cost can be obtained by the sum of all costs generated by each failure mode applied up to a time horizon.

The user cost from maintenance interventions can be classified into the time delay cost, vehicle operating cost, traffic accident cost, environment cost, etc. (Berthelot, *et al*. 1996). This paper considers the vehicle operating cost and the user delay cost extending the driver delay cost considered in the exiting study to all users riding in the vehicle. To make a reasonable estimation of the user cost, the traffic analysis and regression analysis are performed for developing a regression model (KICT 2006).

2.3. Optimal maintenance scenario generation

An optimal maintenance scenario could depend mainly on the budget of the bridge agency and the importance level of the bridge performance. Also, the satisfied maintenance scenario should be decided so as to balance different objectives such as the improvement of the structural performance and the reduction of the maintenance cost. A single optimal maintenance plan computed by a single objective cannot satisfy the specific requirement of optimal tradeoff between the life-cycle maintenance cost and the structural performance during the lifetime. As an alternative approach for this maintenance plan, the combination of the available maintenance interventions can be applied to generate an optimal maintenance scenario during the period of time considered (Liu and Frangopol 2005, Furuta, *et al.* 2004). For the life-cycle maintenance of a deteriorating bridge, this study generates a set of optimal maintenance scenarios, minimizing the LCC and maximizing the reliability and condition as the separated objective functions based on the Pareto optimum concept. A multi-objective genetic algorithm (GA) is used for generating a set of various maintenance scenarios.

3. Optimal maintenance scenario

The bridge agency would require the optimal maintenance scenario to minimize the maintenance cost generated during the life cycle of a bridge and to maximize the specific performance close to the target required by a bridge manager. The optimal maintenance scenario could depend mainly on the budget of the bridge agency and the importance level of the bridge performance. Also, the satisfied maintenance scenario should be decided so as to balance different objectives such as the improvement of the structural performance and the reduction of the maintenance cost. The existing method has established the maintenance strategy as follows: It creates a profile with the condition level for each structural member by considering the correlation between the alternatives for each bridge member that consists of the life cycle activity profile (LCAP) which occurs. Then it executes the economical analysis for each alternative LCAP (MOCT/KISTEC 2000). Therefore, the existing maintenance strategy has fundamental limits in selecting the optimal maintenance scenario.

3.1. Multi-objective optimization

Most of the existing bridge maintenance system tools also focus on minimizing the life-cycle maintenance cost and simultaneously give the restriction of the structural performance for deteriorating bridges (KICT 1999, Thompson, *et al.* 1998, Miyamoto, *et al.* 2000). A single optimal maintenance plan computed by a single objective cannot satisfy the specific requirement of optimal tradeoff between the life-cycle maintenance cost and the structural performance during a lifetime. As an alternative approach for this maintenance plan, the combination of the available maintenance interventions can be applied to generate an optimal maintenance scenario during the period of time considered (Liu and Frangopol 2004, 2005, Furuta, *et al.* 2004).

Using the life-cycle maintenance of a deteriorating bridge, this study generates a set of optimal maintenance scenarios that minimize the LCC and maximize the reliability and condition as separated objective functions based on the Pareto optimum concept. A multi-objective genetic algorithm (GA) is used for generating a set of various maintenance scenarios verifying the optimal tradeoff solution among the objective function that conflict between cost and performance. The problem generating maintenance scenario considered in this paper can be formulated in the multi-objective optimization problem as follows:

Objective:

$$F_1 = C_T^p = \sum_{t=t_p}^{T} C_t^p \rightarrow \text{min.} \tag{3}$$

$$F_2 = \rho_t = \min[\rho_{t_p}, \rho_{t_p+1}, \rho_{t_p+2}, \rho_T] \rightarrow \text{max.} \tag{4}$$

$$F_3 = \beta_t = \min[\beta_{t_p}, \beta_{t_p+1}, \beta_{t_p+2}, \beta_T] \rightarrow \text{max.} \tag{5}$$

Subject to:

$$g_t(\cdot) \leq 0 \qquad i = 1,2,..., N_s \tag{6}$$

where C_T^p = current value of total life-cycle cost; ρ_t = lifetime condition index; β_t = lifetime reliability index; t_p = present time; T = total period of lifetime; $g_i(\cdot)$ = i-th constraint related to the budget, performance or specific requirements of bridge manager; N_s = number of constraints.

Bridge managers will face the problem of selecting an alternative scenario among many suggested scenarios. Ultimately, the decision for the final maintenance scenario will rely on the bridge manager. This study applies a fitness function to provide the optimal tradeoff solution, which is possible not only for the case of an optimal tradeoff solution among conflicting objective functions but also for the case of the bridge manager's specific requirements and constraints. In multi-objective combinatorial optimization studies, the maintenance problem of a bridge that systematically consists of the various members has considered only a single member until now. This study proposes an advanced technique to select the optimal tradeoff maintenance scenario over an entire bridge system considering the subordinate relation from the replacement of bridge members for securing a realistic application (Park 2006).

3.2. Optimal maintenance system framework

With an evaluation and cost model related to performance, including the condition index and the reliability index, this study introduces a systematic procedure for selecting the optimal tradeoff solution among conflicting objectives based on the multi-objective GA. A MCS method is used to consider the

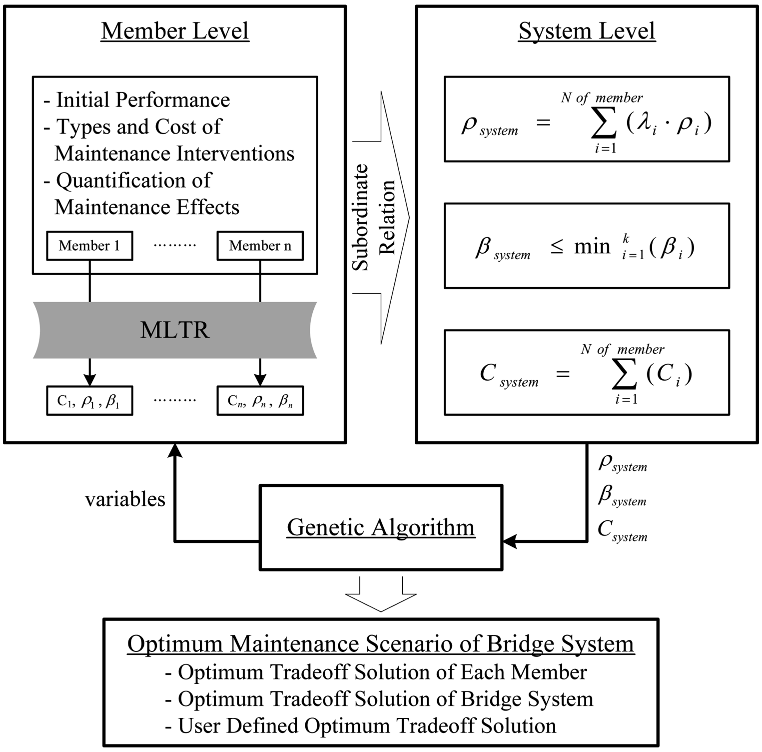


Fig. 2 Concept of proposed system framework

probabilistic structural performance because of the uncertainty related to the deterioration of each bridge member and the uncertainty of the life-cycle maintenance cost. This process applies to all parts considered in the members of a bridge. In case that the replacement of a member influences the other members, a maintenance scenario of the bridge system is proposed considering the subordinate relation between members, that is, the influenced members should be replaced at the same time. Also, the cost items applied to generate the optimal maintenance scenario can be selectively considered and a suitable optimal maintenance scenario for the considered cost items can be proposed. This study developed a GA_MLTR with the GA-based program using MLTR by the suggested methods. Fig. 2 shows the proposed optimal maintenance system framework.

4. Program generating optimum maintenance scenario

With the evaluation and cost model related to the performance, including the condition index and the reliability index, this study developed a systematic procedure for selecting the optimal tradeoff solution among conflicting objectives based on the multi-objective GA. The results of the analysis are expressed as the annual maintenance intervention, that is, the maintenance scenario during a period of time. A Monte Carlo simulation (MCS) method is used to consider the probabilistic structural performance from the uncertainty related to the deterioration of each bridge member and the uncertainty of the life-cycle maintenance cost. This process is applied to all parts considered in the members of a steel bridge.

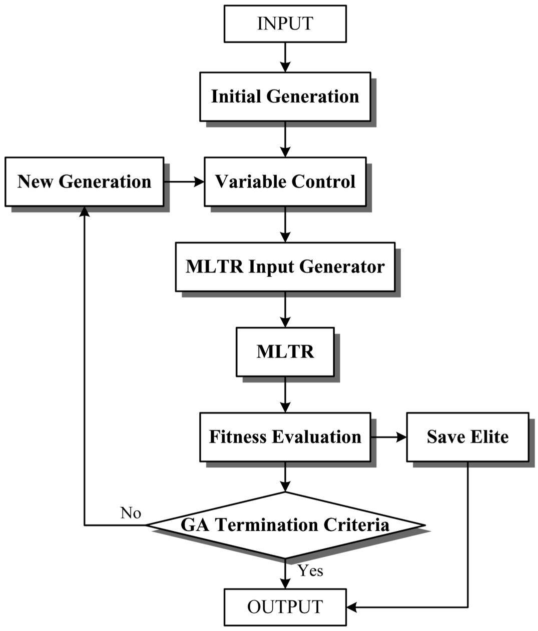


Fig. 3 GA_MLTR flow chart

The developed program, called GA_MLTR, is based on GA and MLTR (Kong and Frangopol 2001), which is an analysis tool for the lifetime performance and cost. The developed program is conceptually described in Fig. 3.

The input data of GA_MLTR is classified into the model data related to the deterioration, repair/retrofit model, user cost and the data defined by design variables and constrains. The deterioration model and the repair/retrofit model data are created. The type and time for applying the replacement and repair/retrofit method and the performance changed by the applied method are considered as the design variables. The application time is automatically calculated by the program. The bridge manager's requirements, such as the maximum performance level and the minimum maintenance cost, can be input selectively.

Each module of GA_MLTR can be briefly explained as follows: The genetic algorithm (GA) module generates a set of scenarios by producing a random number for the design variables to maximize a fitness value using the fitness function (objective function) and then generates the scenario repeatedly in accordance with the defined number of population and generations. The GA module, including MLTR, is composed of the Initial Generation module that generates the initial population, the Fitness Evaluation module that calculates the fitness function and draws out the non-dominated elite solutions, and the New Generation module that generates a new population.

The New Generation module generates a new population through the process of selection, crossover and mutation in the case of not satisfying the stop-constraint of the GA. The Variable Control module controls the scenario of replacing a subordinate member when a super ordinate member is replaced by considering the correlation between members. Furthermore, when the replacement or the repair/reinforcement method is applied within the same member, it controls the scenario so as not to repeat the same method considering the minimum iteration period. With this process a realistic maintenance scenario can be formulated. The MLTR Input Generator module generates a MLTR input statement for analyzing the maintenance cost and performance within the period of maintenance using the scenario that is modified by considering the correlation among members and the minimum repeat time of the replacement and repair/retrofit method. The MLTR module analyzes the maintenance cost and performance profiles for the period of maintenance by using the input generated from the MLTR Input Generator module. The Fitness Evaluation module calculates the fitness function value for the objective functions using the maintenance cost and performance computed by the MLTR and draws out a set of elite solutions by comparing the calculated fitness function value for each population. There are Save Elite modules that store an elite set for each generation extracted from the Fitness Evaluation module and generates a Pareto Solution for all generations and the Output module that computes the fitness function for the entire solution area for the Pareto Solution stored by the Save Elite module. The priority order of scenarios will be calculated by the fitness function value, and if there are constraints about the cost and performance by the user the priority order will be calculated according to this constraint. Finally, it reanalyzes the high ranking maintenance scenarios in the priority order of the calculated scenarios and gives a profile about the maintenance cost, user cost, failure cost and the performance for each scenario.

5. Analysis example

The developed GA_MLTR program can generate maintenance scenarios for each individual member of the bridge such as the slab, pavement, girder, etc. However, the bridge as a system structure has the subordinate relationship among members that the replacement of a member causes the replacement of other members, so the simple combination of an optimal maintenance scenario for each member does not mean an optimal maintenance scenario for the entire bridge system. Therefore, the maintenance scenario for the system level simultaneously considering the maintenance interventions in each member can become a realistic maintenance plan.

For studying the applicability of the developed method, this paper chose a steel box girder bridge that was built in 2001 with a length of 45 m, width of 19.5 m and 3-steel boxes in a simple span. The period of analysis is considered to be 50 years after completion of the bridge construction. The slab and pavement are considered in the analysis process to generate a system maintenance scenario, and then the quantification of the deterioration model and the repair/retrofit effect of the members are considered by applying a condition evaluation model for each member. The maintenance interventions to the slab are the epoxy injection, deck waterproofing, FRP attaching and replacement. In case of pavement it considers the surface treatment, patching, cutting overlay and re-pavement. Only the direct costs from the maintenance interventions are considered and each of the direct costs is estimated by the references and surveys of professional engineers (KICT 2006).

The number for the population and generations applied to the GA_MLTR execution is 1,000 individuals and 30 generations and the probability of crossover and mutation is 50% and 5%, respectively. Among the solutions, the elite solutions kept in each generation are distributed with respect to two objectives of the condition index and cost as shown in Fig. 4. It shows that the entire solution set of the system level has a limit in the performance improvement in accordance with the minimum iteration period for the replacement and repair/retrofit defined in each member.

Among the solutions of elite group, the ranking order of the optimal tradeoff scenario is shown in Table 1. As for the degree of importance, which is the ratio of each cost and the ratio of each condition against the minimum and maximum value among solutions, respectively, the solution at ranking 2

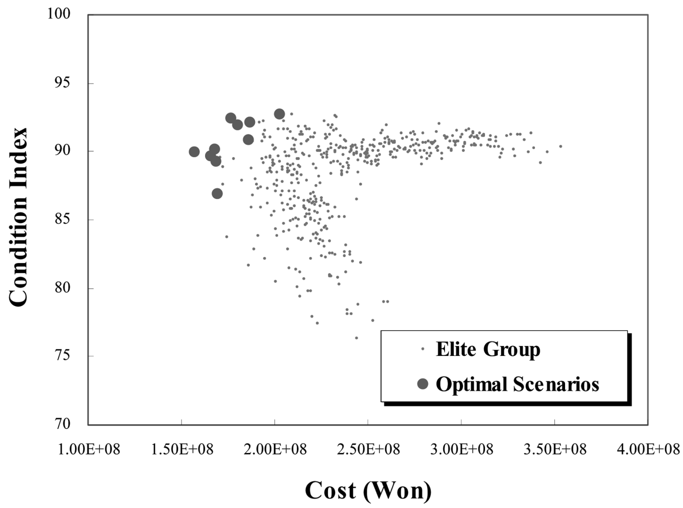


Fig. 4 Solution set for elite

Table 1 Ranking list of optimal tradeoff maintenance scenarios

Rank	Cost (Thousand won)	Condition index	Degree of importance	
			Cost	Condition
1	176,709	92.4	0.902	0.988
2	157,346	90.0	1.000	0.850
3	180,740	91.9	0.882	0.959
4	187,179	92.1	0.849	0.968
5	165,794	89.6	0.957	0.833
6	202,743	92.7	0.771	1.000
7	167,784	90.2	0.947	0.862
8	169,217	86.9	0.940	0.679
9	169,143	89.3	0.940	0.813
10	185,978	90.8	0.856	0.898

would be a single-objective optimal solution based on a minimum LCC and it shows a relatively low life-cycle condition index.

Table 2 shows the annual maintenance scenarios of the slab and pavement in priority order up to ranking 3, which is derived from each tradeoff solution shown in Table 1. The system level analysis uses the subordinate relationship along with the replacement of a specific member. For instance, pavement has to be replaced if slabs are replaced. As a result, system level analysis considering subordinate relationship between members can generate more reasonable maintenance scenarios.

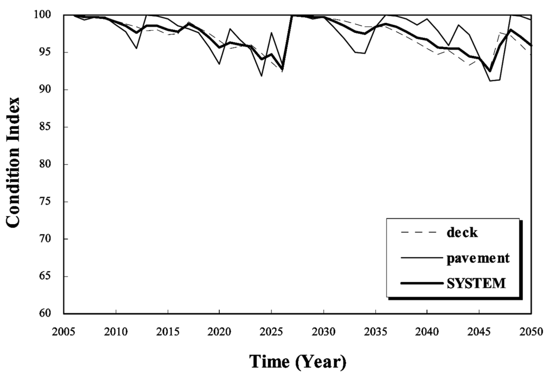
During the period of analysis, the maintenance cost and condition index of Scenario 1 are shown in Fig. 5. According to Fig. 5(a), which shows the condition index profile during the lifetime of each member and system, it can be said that the bridge condition depends on the condition of slab because the slab is governed to calculate the system condition index in accordance with the detailed guideline for safety inspection and precise safety diagnosis (MOCT/KISTEC 2003). According to Fig. 5(b),

Table 2 Annual maintenance scenarios

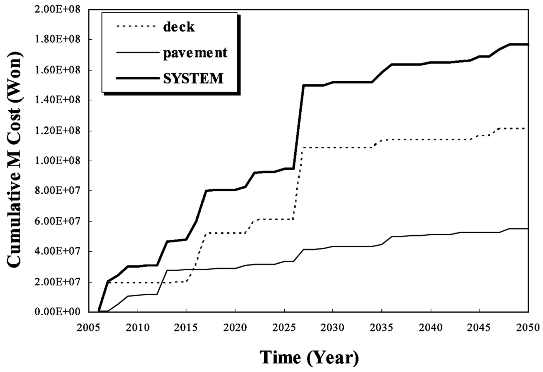
No.	Year	Scenario 1		Scenario 2		Scenario 3	
		Slab*	Pave.**	Slab	Pave.	Slab	Pave.
1	2006	1	1	1		2	3
2	2007	2		3	3		
3	2008		3			1	1
4	2009			2	1		
5	2010		2		2		
6	2011		1				
7	2012					2	
8	2013		4		2		3
9	2014	1			1		
10	2015		1	1	3		
11	2016	2			2		2
12	2017	3	2		1	1	4
13	2018		1			2	
14	2019				2		
15	2020				1	3	1
16	2021		3				3
17	2022	2	1	2	2		
18	2023	1	2		1		1
19	2024						2
20	2025		3		4		
21	2026				1		
22	2027	4	4			1	
23	2028			1	3		2
24	2029		1	2		4	4
25	2030	1	3		1		
26	2031			3			
27	2032					2	2
28	2033				1		3
29	2034		2	1	3		
30	2035	2					
31	2036	1	4				
32	2037		1	4	4		
33	2038		2		1	2	4
34	2039				3		3
35	2040		3	2			
36	2041						
37	2042	1		1	2		
38	2043						1
39	2044		1				
40	2045	2			3	2	3
41	2046			2	1		2
42	2047	3	2		4	1	
43	2048	1	4			3	1
44	2049			1	1		
45	2050						2
Condition Index		92.43	91.18	87.70	86.11	91.55	90.20
LCC (10^3 won)		121,321	55,388	112,575	44,771	123,384	57,357

*Maintenance interventions for the slab 1: Epoxy injection method, 2: Surface waterproofing method 3: FRP boding method, 4: Replacement

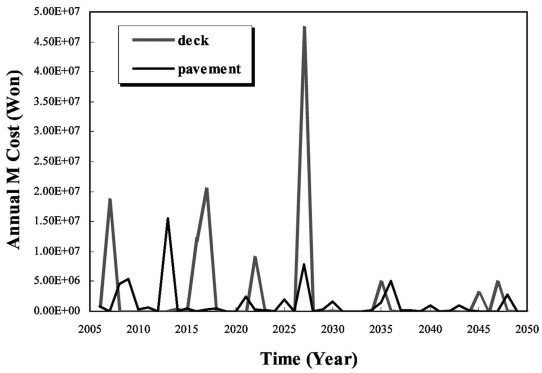
**Maintenance interventions for the pavement 1: Surface treatment method, 2: Patching method, 3: Cutting overlay method, 4: Re-pavement



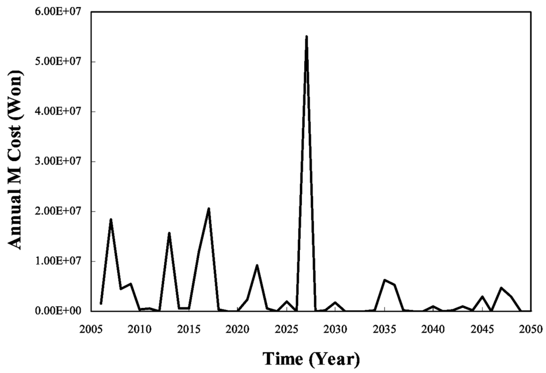
(a) Change of condition index



(b) Change of accumulated maintenance cost

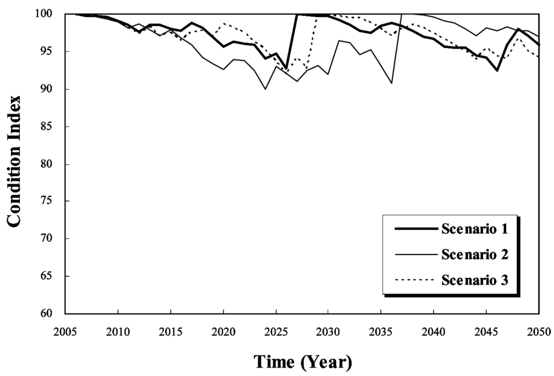


(c) Change of annual maintenance cost (for each member)

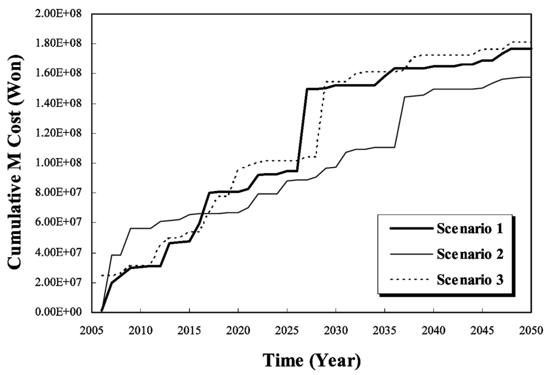


(d) Change of annual maintenance cost (system)

Fig. 5 Change of condition index and cost in Scenario 1



(a) Comparison of condition index



(b) Comparison of maintenance cost

Fig. 6 Comparison of condition index and cost per scenario

which shows the cumulative maintenance cost of the member and the system, the maintenance cost in the year generating a member replacement increases rapidly and the expected cost converted into the current value increases slowly with the effect from the discount rate. Fig. 5(c) and Fig. 5(d) describe the profiles of the annual maintenance cost for each member and system. Fig. 6 shows a graph of the condition index profile and the cumulative maintenance cost for the lifetime of the bridge in accordance with the annual maintenance scenario presented in Table 2. If the scenarios in Table 2 secure a certain level of performance to manage the bridge, the bridge manager can select an appropriate scenario to compromise the maintenance cost at a certain period of time with the given budget with reference to Fig. 6(b). It is possible to select not only the presented scenario in Table 2 but also all generated scenarios satisfying the requirement of the bridge agency.

6. Conclusions

Unlike traditional bridge maintenance methods aiming to find out a single maintenance scenario minimizing the life-cycle cost, this paper developed a practical method and a computer program providing a number of tradeoff maintenance scenarios between two conflicting objectives considering not only the life-cycle cost but also the life-cycle performance. The developed program has applied to an existing bridge to investigate the feasibility of the proposed method. The main conclusions from this study are as follows:

(1) For the realization of the preventive maintenance system, this study proposes a method for generating the optimal tradeoff maintenance scenarios between the conflicting objectives, cost and the performance, by considering the change of performance as well as the life-cycle maintenance cost during the bridge lifetime. This method should propose the optimal maintenance scenarios satisfying the various requirements and constraints of the bridge agency.

(2) The developed program through the application of genetic algorithm including the life-cycle performance and the cost analysis program can generate the optimal tradeoff maintenance scenarios for not only in the level of bridge member, but also in the level of bridge system.

(3) Through applying the developed program to the existing bridge, it was found that the maintenance scenario with the system level can be generated through the life-cycle analysis and reasonable annual optimal maintenance scenarios can be generated by considering the subordinate relationship in accordance with the replacement between members.

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