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온실가스 배출을 고려한 생애주기비용 기반의 CBM 모형 연구

CBM Based on Life-Cycle Cost Analysis Considering CO_2 Emission

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Abstract Condition-based maintenance (CBM) is one of preventive and predictive maintenance (PPM)policies of which objective is to find the optimal maintenance activity based on the current state and predicted future state. Since CBM chooses an optimal maintenance based on the life-cycle cost analysis for a planned life span, there is a cost evaluation part in the optimization part. This study proposes an environmental sustainable CBM policy which contains environmental cost in life-cycle cost evaluation process. The environmental cost of the maintenance activities is evaluated based on the total amount of Carbon-dioxide emission during the production and construction process of asphalt mixture. In the result part, this study shows the comparative maintenance results between CBM and another maintenance policy.

Keywords Condition-based maintenance, life-cycle cost analysis, environmental cost

상태기반 보수는 예방 및 예측 보수 방법 중 하나로서, 인프라 현재 상태와 예측되는 미래 상태를 기반으로 최적의 보수 활동을 찾는 방법론이다. 상태기반 보수가 생애주기 비용을 기초로 최적의 보수활동을 찾기 때문에, 상태기반 보수는 생애주기 비용 산출식이 존재한다. 이번 논문에서는 생애주기 비용 산출식에 이산화탄소 배출량에 의한 환경 비용을 추가하여, 인프라 관리로 인한 환경 영향을 고려하였다. 환경 비용은 해당 인프라 재료의 생산과 공사 과정 전체에서 나오는 이산화탄소 양을 기초로 측정되었다. 시뮬레이션 파트에서는 40년 동안의 인프라 상태 변화와, 100가지 시뮬레이션 결과의 생애주기 비용을 이산화탄소 환경 비용을 고려한 시간기반 보수 결과와 비교하였다.

주요어 : 상태기반 보수, 예방 및 예측 보수, 생애주기 비용분석, 환경비용

1. Introduction

As a use of infrastructure or a system of infrastructures increases, they begin to worsen lowering performance and influenced by the ageing effect. Continuous maintenance is needed to prevent deterioration of infrastructure which can imply social disaster. Before the 1950s, infrastructure was managed with reactive maintenance, which does not consider the target system before critical failure. Even if it repaired earlier with minor abnormalities, it would not cost a lot, since target system have already done critical damage, the agency has to spend a lot of money on not only the failed part but the near part which affected. As the expenditure has increased, minimum total life cycle cost of the target system has become the interesting topic. As a consequence, preventive and predictive maintenance (PPM) has been introduced. It aims to minimize the total life cycle cost of the infrastructure system with proactive repair actions. Among various approaches based on PPM, condition-based maintenance (CBM) is the representative maintenance strategy.

On the other hand, construction and maintenance of infrastructures have an effect on environment. Several studies are conducted to follow international trend such as worldwide emissions standards trying

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to reduce greenhouse gas emission. In addition, social cost of carbon is used to estimate the climate benefits and to make a policy by many federal agencies. Although interest in environmental effect of construction increases, however, no research about pavement maintenance considering the effect of CO2 is conducted yet. This study, therefore, models CBM considering environmental effect and compares the analysis result to that of TBM.

Previous Research

Some researchers have focused on minimizing life cycle cost which is not only maintenance cost but the sum of the construction, maintenance and the destruction cost. Kong and Frangopol [1] suggested a method for evaluating the expected life cycle maintenance cost based on a modified event tree analysis. Liu and Frangopol [2] concerned both life cycle maintenance cost, and lifetime condition and safety level to solve the maintenance planning of bridges as multi-objective optimization. More recently, a method for maintenance optimization with two-stage bottom-up approach is developed by Yeo, Yoon, and Madanat [3, 4] It divides into facility-level optimization and system-level optimization which can reflect the reality imposing the budget constraint.

Since various greenhouse gases such as CO2, CH4, and N2O is emitted during construction, indiscriminate maintenance may bring out a harmful influence on environment. CO2 emissions in building construction field according to the selection of materials are studied by Andrew and Brian [5] and Hammond and Jones [6]. In pavement field, Rajib and John [7] conducted laboratory study on CO2 emission from asphalt the major material of pavement and Bo, Chunli, Guangkai, Wenying, and Yaowen [8] researched evaluation system for CO2 emission of hot asphalt mixture which emit approximately 90% of the total carbon emission in pavement construction. Many researchers concerned social cost (SC) of CO2 [9], and this estimated SC is used for decision making.

In this paper, CBM and (Time-Based Maintenance) are compared considering environmental effect and the condition of infrastructure and the total life cost will be analyzed and compared. Environmental factor is concerned as an SC of CO2 emitted during whole life cycle including construction, maintenance, and destruction.

2. Methodology

Optimal Solution Method for Condition-Based Maintenance

The condition information obtained by inspection or monitoring is applied to the process of determining the optimal solution in CBM. And it is used for predicting the future condition of an infrastructure. The prediction information of the future condition helps to determine the highest level of efficiency of maintenance actions and it saves a lot in terms of life-cycle cost. In this research, CBM needs to find the optimal maintenance activity for each year based on the inspection result. And the inspection and the maintenance activities are applied every year at the beginning of the year.

The CBM optimization problem can be solved by various different methods. The dynamic programming is one of the most widely used solution algorithms for the proposed problem, especially the stochastic deteriorating problems. Dynamic programming for optimal activity a^* and its expected cost-to-go V^* can be formulated as the following equations (Yeo et al., 2013).

$$a^*(i,t) = \operatorname{argmin}\{C_a(a,i) + C_{u_m}(a) + C_{u_r}(i) + \alpha \textstyle\sum_{j\in S} V(j,t+1)P_a(i,j)\} \quad (1)$$

$$V^*(i,t) = \min\{C_a(a,i) + C_{u_m}(a) + C_{u_r}(i) + \alpha \textstyle\sum_{j\in S} V(j,t+1)P_a(i,j)\} \quad (2)$$

where,

$C_a(a,i)$: repair cost for activity *a* in state *i*

$C_{u_m}(a)$: user cost during the maintenance activity *a*

$C_{u_r}(i)$: user cost in state *i*

A : set of maintenance activities, A ={a_1, a_2, a_3}

S : set of system condition, S ={$1, \ldots, 10$}

$P_a(i,j)$: transition probability from state *i* to *j* under maintenance activity *a*

Fig 1 illustrates a dynamic programming solution method and it has three maintenance activities and 10 states of a given infrastructure. The CBM tries to find the optimal solution for each year based on the expected cost-to-go from the current year t to the final year T. And the expected cost-to-go is calculated from the condition of the facility. By repeating the process, we can get the optimal maintenance activity at year 1 that minimizes the expected life-cycle cost, which is the expected cost-to-go from year 1 to T.

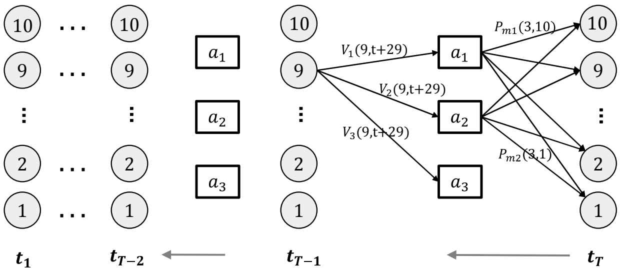


Fig. 1 Dynamic programming solution for life-cycle cost optimization under stochastic deterioration

The Social Cost of CO2 During Construction

To consider social cost of CO2 during construction, several information is needed: amount of CO2 emission per unit material of pavement, social cost of CO2, and total construction cost per same unit. One ton of asphalt is concerned as a unit material of pavement. Bo, Chunli, Guangkai, Wenying, and Yaowen (2015) calculated carbon emission translating other greenhouse gas to CO2 using CO2 equivalents. Thereupon, CO2 emission is 0.03ton per one ton of asphalt. After then, calculated CO2 emission is translated in SC: $56 per one ton of CO2 (discount rate 2.5%avg) (Interagency Working Group on Social Cost of Carbon, 2013). Since construction cost is various according to the site, construction cost of one ton of asphalt is estimated as an average of 10 random sites. As a result, construction cost is $360 per one ton of asphalt. Ratio of construction cost and SC of CO2 is calculated about 214:1.

Simulation Comparison of TBM and CBM

For evaluating the proposed optimization algorithm and demonstrating the applicability to realistic problems, a highway pavement section with transition probability matrix and action costs were generated.

Test System Creation

A virtual highway pavement system, which is created for the simulation, consists of a single section. Each state of the section is represented by discrete numbers from 1 to 10, and simulations are run stochastically based on the transition probability matrix. The planning horizon T and the interest rate were set to 40 and 5%. It is assumed that the maintenance agency has three maintenance activities: do nothing, repair, and reconstruction. To get the information of the transition probability matrix and cost for maintenance activities, US Department of Transportation report (1998) is referred.

Table 1 shows the agency activity costs and the social cost for CO_2 for CBM and the acceptable range of the state for both CBM and TBM. Note that the pavement states lower than four are assumed to be unacceptable by the low serviceability, which is incorporated as a constraint in optimization procedures. For the TBM cases, it is assumed that the same maintenance activity would be conducted on the pavement section and the maintenance cost for repair action was equally set to 100. Based on the analysis of CO_2 emission, the ratio of construction cost and SC of CO_2 is set to 214:1 and ***Ecost1~Ecost3*** has the result.

Table 1 Activity costs and Social cost for CO_2 ($1,000)

Activity cost	**Maintenance Activity**			***a_1***	***Ecost1***	***a_2***	***Ecost2***	***a3***	***Ecost3***
	State	10	**Acceptable**	0	0	30	0.14	500	2.34
		9		0	0	70	0.33	500	2.34
		8		0	0	110	0.51	500	2.34
		7		0	0	150	0.71	500	2.34
		6		0	0	190	0.89	500	2.34

		5		0	0	230	1.07	500	2.34
		4		0	0	270	1.26	500	2.34
		3	**Unacceptable**	0	0	310	1.45	500	2.34
		2		0	0	350	1.64	500	2.34
		1		0	0	390	1.82	500	2.34

There are three transition matrices and they provide the probabilities of state transitions in a pavement segment after a maintenance activity over 1-year period. The matrices shown below are the transition probability matrices for do nothing (P1) and repair (P2). For reconstruction activity, P3 is defined as a column vector with P3 (i, j) =1, and P3 (i, j ≠ 1) =0.

$$P_1 = \begin{bmatrix} 0.68 & 0.32 & & & & & & & & \\ & 0.78 & 0.22 & & & & & & & \\ & & 0.75 & 0.25 & & & & & & \\ & & & 0.67 & 0.33 & & & & & \\ & & & & 0.66 & 0.34 & & & & \\ & & & & & 0.68 & 0.32 & & & \\ & & & & & & 0.5 & 0.5 & & \\ & & & & & & & 0.55 & 0.45 & \\ & & & & & & & & 0.49 & 0.51 \\ & & & & & & & & & 1.00 \end{bmatrix} \qquad P_2 = \begin{bmatrix} 0.80 & 0.20 & & & & & & & & \\ 0.68 & 0.32 & & & & & & & & \\ & 0.78 & 0.22 & & & & & & & \\ & & 0.75 & 0.25 & & & & & & \\ & & & 0.67 & 0.33 & & & & & \\ & & & & 0.66 & 0.34 & & & & \\ & & & & & 0.68 & 0.32 & & & \\ & & & & & & 0.5 & 0.5 & & \\ & & & & & & & 0.55 & 0.45 & \\ & & & & & & & & 0.49 & 0.51 \end{bmatrix}$$

In addition, annual inspections are performed at the beginning of the year under CBM policy, and the cost is set to 10 for both CBM and TBM. Table 2 shows the salvage value and penalty cost for each state. Salvage value provides the remaining value of the infrastructure system at the end of the analysis period, so it is treated as a negative cost. The penalty cost or the user cost, $C_{u_{i_t}}(t)$ is assumed to be incurred from the lower condition of the pavement. The user costs derived from all these inconveniences can be included in the penalty cost and user cost for each state is shown in the Table 2. Not to allow the state of 4, which possesses some potential danger of failure, high value of penalty cost for TBM is set, and the solutions with the states lower than 4 in CBM are not allowed.

Table 2 Salvage value and penalty cost for the test infrastructure system

State	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
Salvage Value	-800	-700	-500	-200	-150	-120	-100	-80	-50	-30
Penalty Cost	0	0	0	40	80	100	210	350	800	1500
								Not Allowed in CBM		

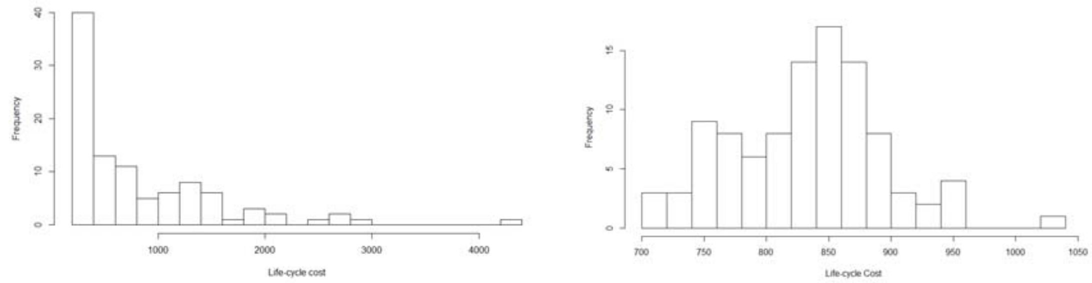
Condition Transition under TBM and CBM Policy

(a) TBM condition transition examples over planning horizon (b) CBM condition progress examples over planning horizon

Fig. 2 Two-examples of condition transition of TBM and CBM

This study applied the optimal solution algorithms for the test system under the TBM and CBM policy. The initial state of the test system is set to state 8. The conditions of the pavement are compared for 40 year planning horizon. Since the infrastructure conditions change randomly for each time period based on the transition probability matrices in each simulation run, different condition progress results are obtained for each simulation run. Fig. 2 shows two examples showing the condition progress under the TBM and CBM policy. The TBM optimization found the optimal repair interval and the reconstruction interval is set as 5 year and 10 year in this example. In Fig. 2(a) the infrastructure conditions remain between state 6 and 8 for 35 years and are deteriorated after 35 years. The deterioration after 35 years is not treated as fail, since its life span is 40 years. Compared to TBM, as shown in the Fig. 2(b), the CBM keeps its state as 8 to 10 with the minor partial repair maintenance action. Since the cost for the minor repair is cheap, the CBM has advantages.

Life-Cycle Cost Comparison



(a) Life-cycle cost distribution from TBM (b) Life-cycle cost distribution from CBM

	Min	1st Qu.	Median	Mean	3rd Qu.	Max.
TBM	213.7	279.6	546.3	822.0	1197.0	4334.0
CBM	703.9	792.3	835.6	833.0	868.6	1027.0

Fig. 3 Life-cycle result for 40 years

The life-cycle costs are evaluated by running 100 simulation runs to compare the cost efficiency of the two maintenance strategies. Fig. 3 compares the life-cycle cost distribution for TBM and CBM. TBM has higher life-cycle cost and greater cost deviation than CBM. As the high life-cycle cost means less cost efficiency, the high variation in cost indicates less reliability of the policy. To show the relationship between the average annual cost and life-cycle costs for TBM and CBM, 300 samples were evaluated. The average annual cost is defined as the average cost that the agency and users pay annually for 40 years. Figure 12 compares the results under TBM and CBM: Black marks are for TBM, and grey ones are for CBM. In TBM cases, the range of the life-cycle cost was [213.7, 4334.0], and that of the CBM was [703.9, 1027.0] which is much narrow than that of TBM. Since the mean of the life-cycle cost is similar, the skewness and the range can be the comparison standard.

3. Conclusion

This study develops the CBM policy which consider the environmental effect using the CO_2 emission. The cost for CO_2 emission is analyzed and applied. From the comparison of the simulation results of condition transition and the life-cycle cost show that the annual inspection process of CBM helps to choose various choices among 10 maintenance actions and this annual maintenance keeps the state of the infrastructure high as 8 to 10. In addition, from the life-cycle cost distribution of the CBM, which is similar to the normal distribution, it is noticeable that the agency can manage the infrastructure in stable and expectable range when it use CBM policy.

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Reference

[1] Kong, J. S., & Frangopol, D. M. (2003) Evaluation of expected life-cycle maintenance cost of deteriorating structures. Journal of Structural Engineering, 129, 682–691.

[2] Liu, M., & Frangopol, D. M. (2005) Multiobjective maintenance planning optimization for deteriorating bridges considering condition, safety, and life-cycle cost, Journal of Structural Engineering, 131, 833–842.

[3] Yeo, H., Yoon, Y., & Madanat, S. (2010) Maintenance optimization for heterogeneous infrastructure systems: Evolutionary algorithms for bottom-up methods. In: K. Gopalakrishnan & S. Peeta (Eds.), Sustainable and resilient critical infrastructure systems: Simulation, modeling, and intelligent engineering. (pp. 185–200). Berlin: Springer-Verlag.

[4] Yeo, H., Yoon, Y., & Madanat, S. (2013). Algorithms for bottom-up maintenance optimisation for heterogeneous infrastructure systems. *Structure and Infrastructure Engineering, 9*, 317–328.

[5] Andrew H. Buchanan and Brian G. Honey (1993) Energy and carbon dioxide implications of building construction, *Energy and Buildings, 20*, 205-217.

[6] G. P. Hammond and C. I. Jones (2008) Embodied energy and carbon in construction materials , Proceedings of the Institution of Civil Engineers, 2, 87-98, DOI: 10.1680/ener.2008.161.2.87

[7] Rajib B. Mallick & John Bergendahl (2009) A laboratory study on CO2 emission from asphalt binder and its reduction with the use of warm mix asphalt, *International Journal of Sustainable Engineering, 2:4*, 275-283, DOI: 10.1080/19397030903137287

[8] Bo Peng, Chunli Cai, Guangkai Yin, Wenying Li, and Yaowen Zhan (2015), Evaluation system for CO2 emission of hot asphalt mixture, *Journal of traffic and transportation engineering, 2(2)*, 116-124.

[9] Richard Clarkson and Kathryn Deyes (2002), Estimating the Social Cost of Carbon Emissions, Department for Environment, Food & Rural Affairs, Government Economic Service Working Paper 140.

[10] Interagency Working Group on Social Cost of Carbon (2013) Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, United States Government.