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A model for concurrent maintenance of bridge elements

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ABSTRACT

Maintenance activities on existing bridges are important for bridge safety and management. However, maintenance activities cause traffic jams and detours, and thus increase user costs. To reduce user costs resulting from maintenance activities while maintaining bridge elements in good condition, we introduce the concept of “concurrent element maintenance.” The concurrent maintenance concept attempts to integrate maintenance timings of different elements of a bridge to reduce user costs over the bridge's life cycle. The proposed model adopts constraint programming as the search algorithm for optimizing the maintenance strategy of any bridge. An example using real data for a reinforced concrete highway bridge is presented. Sensitivity analysis of the discount rate investigates its influence on the life-cycle cost. The results demonstrate that the proposed model is effective for reducing the user costs as well as the total life-cycle costs.

1. Introduction

The construction of the transportation network is the most basic and key contribution to the nation's economy. All countries put their best resources and efforts into building up their own transportation network. After years of construction, concerns are less and less related to new construction projects but are more and more dramatically related to the maintenance of existing transportation facilities. Bridges play an important role in the transportation facilities. Some serious cases of old bridge collapses causing huge loss of life and blockages in the transportation network, such as the Silver Bridge in Ohio, USA in 1967 and the Feng-Gang Bridge in Taiwan in 2005, have drawn more and more attention to bridge maintenance issues, especially on aging bridges.

A maintenance plan for aging structure is essential to ensure a bridge's safety and serviceability. However, the impact of maintenance actions on the transportation network is much greater than before because of the increased usage of transportation with increased economic and business development. The social cost resulting from the traffic, environmental, and commercial impacts of construction was found to be about 5.5 times the total construction cost [1]. The number of vehicles is increasing, and the traffic impact of construction or maintenance is growing quickly. Thus, arrangement of maintenance activities to reduce the related user impact and cost is essential to society and to decision makers.

Recent research has taken user costs into consideration in construction and maintenance planning. Carr [2] used construction congestion cost systems to estimate the impacts of different traffic maintenance and construction methods in construction projects, as well as to provide decision makers with a better understanding of projects and of drivers' behaviors. Lee and Ibbs [3] simulated traffic volumes for several pavement maintenance strategies and calculated user costs as references for decision makers. Lee et al. [4] investigated the influence of maintenance strategies in the I-710 rehabilitation project on user costs. Related research concluded that the huge social costs of construction or maintenance should be considered in the decision-making process.

To reduce the user costs caused by essential bridge maintenance activities, we propose the concept of “concurrent element maintenance,” in which we try to schedule the maintenance of bridge elements at the same time where possible to reduce the length of disruptions required to perform maintenance activities. A concurrent maintenance model that minimizes the life-cycle costs including agency costs and user costs of a bridge is established.

An example of a bridge considering maintenance activities for three elements is utilized to assess the capability and to validate the proposed model. Moreover, the sensitivity of life-cycle costs to the discount rate is analyzed. The model established provides decision makers with another maintenance strategy to assist in decision making from both users' and agencies' viewpoints.

2. Maintenance management

An essential function for bridge managers is the allocation of limited resources for maintaining deteriorating bridges. Studies of optimal maintenance planning have been conducted with different considerations. Most of the existing research is aimed at minimizing the expected cumulative maintenance cost over the analysis period. Other performance aspects are considered as constraints to ensure

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satisfactory lifetime safety and serviceability levels for deteriorating bridges. Research efforts on single-objective maintenance planning optimization include: Kong and Frangopol [5], who presented a reliability-based life-cycle cost optimization for deteriorating bridges; Morcous and Lounis [6], who minimized the life-cycle cost of an infrastructure network while fulfilling reliability and functionality requirements; Jha and Abdullah [7], who minimized the maintenance cost of roadside appurtenances for an improved highway life cycle; and Nishijima and Faber [8], who aimed to optimize the allocation of budgets for maintaining the operation of a portfolio of structures.

Another approach is to form a multiobjective optimization problem considering all related performance aspects as separate objective functions. Research efforts on multiobjective optimization problems of maintenance planning include: Miyamoto et al. [9], who considered minimization of maintenance cost and maximization of bridge durability and load-carrying capacity for existing bridges; Furuta et al. [10], who treated life-cycle cost, target safety level and service life as separate objective functions for civil infrastructure systems; Liu and Frangopol [11], who constructed a multiobjective optimization model considering trade-offs among life-cycle maintenance cost, condition, and safety levels of deteriorating bridges; and Lee and Kim [12], who considered maximizing recovery effect, maximizing applicability, and minimizing the maintenance cost for deteriorating bridge decks.

In this paper, optimization of the maintenance timing of different elements of a bridge is solved with respect to the objective of minimizing the life-cycle costs, including agency costs and the costs to users of a bridge. From the users' point of view, we attempt to integrate the timing of maintenance of elements through the proposed concept, “concurrent element maintenance,” to reduce the impact on road users. An example using real data for a reinforced concrete highway bridge is presented to demonstrate the effectiveness of the proposed concept.

3. Life-cycle cost analysis

Life-cycle cost analysis is an engineering economic analysis tool useful in comparing the relative merit of competing project implementation alternatives. By considering all the costs incurred during the service life of an asset, this analytical process helps decision makers to select the lowest cost option [13]. Life-cycle cost analysis has been widely applied for selecting maintenance strategies [5–11,14–17]. For example, Zayed et al. [14] applied economic analysis using present value and equivalent uniform annual cost to compare several steel bridge painting systems. Kong and Frangopol [15] evaluated maintenance cost dynamically by using cost functions incorporating time-dependent variables related to the quality of maintenance, and used these functions to obtain the optimal life-cycle maintenance scenario.

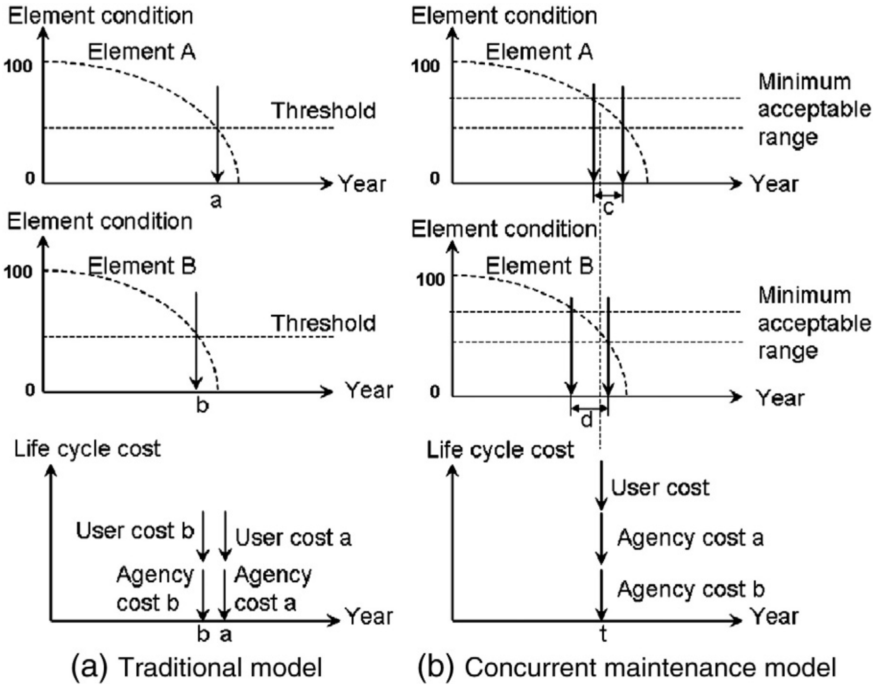
This study establishes a bridge maintenance planning model implementing the proposed concept of concurrent element maintenance as well as life-cycle cost analysis. Both direct and indirect costs are considered in the model. The direct costs, often called agency costs, include costs of material and labor, among others. The indirect cost is the user cost obtained by quantifying service losses such as traffic delays. The most common method for calculating life-cycle cost is the present value method:

$$LCC = \sum_{t=0}^{T} \frac{C_t}{(1+i)^t} \tag{1}$$

where LCC: life-cycle cost; C_t: cost in year t; i: discount rate; and T: analysis period.

4. Concept of concurrent maintenance

The concept of concurrent maintenance attempts to integrate the timings of maintenance of different elements of a bridge to reduce the user impacts and costs caused by maintenance activities. Maintenance activities are implemented for bridge safety while the elements are deteriorating to a threshold; i.e., the minimum acceptable condition of the elements set by the maintenance agencies or decision makers. Usually, maintenance activities are planned element by element to schedule on-time maintenance for each element. For example, two elements, A and B, of a bridge have their own initial condition states and deterioration rates, as shown in Fig. 1(a). Condition states range from 0 to 100, with 100 representing the best condition and 0 the worst condition. As they deteriorate to reach the maintenance



(a) Traditional model (b) Concurrent maintenance model

Fig. 1. Concepts of maintenance models.

threshold, maintenance activities will be performed in years *a* and *b*, respectively, and thus will cause two agency costs and two user costs.

The proposed concurrent maintenance concept modifies the maintenance threshold (i.e., minimum acceptable condition) to a minimum acceptable condition range; therefore, elements would be maintained within a period of time. With the setting of the minimum acceptable condition range, elements A and B can be maintained during time periods *c* and *d*, respectively, as shown in Fig. 1(b). Once there are overlaps between these two maintenance periods, two elements could be scheduled for maintenance at the same time to reduce the interruptions to road users, and thus reduce the user costs, as shown in Fig. 1(b). Considering the integration of maintenance timings of different elements, managers can choose to perform not only just-in-time maintenance but also early maintenance if the maintenance timing can coincide with that of other elements.

5. Research methodology

5.1. Model formulation

By implementing concurrent maintenance, the aim of this study is to optimize the maintenance timing of different elements of a bridge with respect to the objective of minimizing the life-cycle costs including agency costs and user costs.

The following assumptions are made for simplifying the modeling and accelerating the speed of solutions.

1. The deterioration rate of each element is assumed to be constant; i.e., it does not change with time.
2. The maintenance activity only improves the condition of the element, not the deterioration rate of the element.
3. User costs are calculated based on the traffic delays caused by partial lane closures for maintenance activities. The traffic volumes on a bridge before and during the maintenance are assumed to be the same, and the impact of detours is not considered.

Based on these assumptions, each element's earliest and latest time for first maintenance can be decided by its initial condition state and deterioration rate, as well as the upper bound and the lower bound of the minimum acceptable condition range assigned by the decision makers, as shown in Eqs. (2) and (3) below. For each element, within the period of its earliest and latest time, only one type of maintenance can be selected and performed at a time point, as shown in Eq. (4). The effect and the time of that maintenance are shown as Eqs. (5) and (6), respectively. Once the timing and the effect of the previous maintenance are determined, then the earliest and latest time of the following maintenance are decided based on the previous maintenance effect (instead of the initial condition state) and the previous maintenance timing, as shown in Eqs. (7) and (8).

$$ET_{j,1} = (IC_j - UB)/r_j \tag{2}$$

$$LT_{j,1} = (IC_j - LB)/r_j \tag{3}$$

$$\sum_{t=ET_{j,k}}^{LT_{j,k}} \sum_{m=1}^{NM_j} Work01_{j,t,m} = 1 \quad \text{for all } j,\ k \tag{4}$$

$$E_{j,k} = \sum_{t=ET_{j,k}}^{LT_{j,k}} \sum_{m=1}^{NM_j} Work01_{j,t,m} \times Effect_{j,m} \tag{5}$$

$$Year_{j,k} = \sum_{t=ET_{j,k}}^{LT_{j,k}} \sum_{m=1}^{NM_j} t \times Work01_{j,t,m} \tag{6}$$

$$ET_{j,k} = (E_{j,k-1} - UB)/r_j + Year_{j,k-1} \quad \text{for } k = 2\text{~}N_j \tag{7}$$

$$LT_{j,k} = (E_{j,k-1} - LB)/r_j + Year_{j,k-1} \quad \text{for } k = 2\text{~}N_j \tag{8}$$

$ET_{j,k}$: earliest time of the *k*th maintenance of element *j*; $LT_{j,k}$: latest time of the *k*th maintenance of element *j*; IC_j: initial condition of element *j*; *UB*: upper bound of the minimum acceptable condition range; *LB*: lower bound of the minimum acceptable condition range; r_j: deterioration rate of element *j*; $E_{j,k}$: effect of the *k*th maintenance of element *j*; $Year_{j,k}$: year of the *k*th maintenance performed of element *j*; $Work01_{j,t,m}$: boolean variable with the value of 1 if the maintenance type *m* is performed for element *j* in year *t*; $Effect_{j,m}$: maintenance effect of maintenance type *m* of element *j*; NM_j: number of maintenance types of element *j*; N_j: total number of maintenance operations performed for element *j*.

The scheduled time of the last maintenance should exceed the analysis period to ensure the bridge's safety during the analysis period as shown in Eq. (9), where *T* is the analysis period.

$$Year_{j,N_j} \geq T \tag{9}$$

The agency cost for each year is calculated from the costs of the maintenance activities performed in that year:

$$AC_{j,t} = \sum_{m=1}^{NM_j} MC_{j,m} \times Work01_{j,t,m} \tag{10}$$

where $AC_{j,t}$: agency cost of element *j* in year *t*; $MC_{j,m}$: cost of maintenance type *m* of element *j*.

The user cost of each maintenance activity of each element is calculated as Eqs. (11) to (14), including driver delay costs, vehicle operating costs, and accident costs [18].

$$UC_{j,t} = \sum_{m=1}^{NM_j} (DOC + VOC + AC) \times traffic \times D_{j,m} \times Work01_{j,t,m} \tag{11}$$

$$DOC = (L/S_a - L/S_n) \times R_p \tag{12}$$

$$VOC = (L/S_a - L/S_n) \times R_c \tag{13}$$

$$AC = L \times (A_a - A_n) \times C_a \tag{14}$$

$UC_{j,t}$: user cost of element *j* in year *t*; *DOC*: driver delay cost per vehicle per day; *VOC*: vehicle operation cost per vehicle per day; *AC*: accident cost per vehicle per day; *traffic*: traffic volume of the bridge; $D_{j,m}$: duration of maintenance type *m* of element *j*; *L*: length of the bridge; S_a: traffic speed when maintenance performed; S_n: normal traffic speed; R_p: users' time value per hour; R_c: vehicle operational cost per hour; A_a: accident rate when maintenance performed; A_n: normal accident rate; C_a: accident cost.

When more than one element is maintained in the same year, once they are scheduled at the same time, the user cost is determined by the maintenance activity with the longest duration as shown in Eq. (15), where UC_t is the user cost for year *t*.

$$UC_t = \max_j \; [UC_{j,t}] \tag{15}$$

The objective of this study is to minimize the life-cycle costs including agency costs and user costs of a bridge:

$$\text{minimize} \quad LCC = \sum_{t=1}^{T} \sum_{j=1}^{EN} \frac{AC_{j,t}}{(1+i)^t} + \sum_{t=1}^{T} \frac{UC_t}{(1+i)^t} \tag{16}$$

where *EN*: the number of elements of a bridge; and *i*: discount rate.

In this paper, the constraint programming technique is used to solve the model. Constraint programming was developed to solve constraint satisfaction problems starting in the 1970s. It began with

Table 1
Maintenance parameters for example.

Element	Maintenance level	Effect	Agency cost (NT$)[a]	Duration (days)
Pier foundation	I	95	195,000	40
	II	85	174,000	36
	III	75	154,000	32
Girder	I	95	563,000	80
	II	85	504,000	72
	III	75	444,000	63
Bridge deck	I	95	452,000	73
	II	85	404,000	65
	III	75	357,000	58

[a] Costs are indicated in New Taiwan dollars NT$ (TWD) ≒ US$0.03 as of July, 2009.

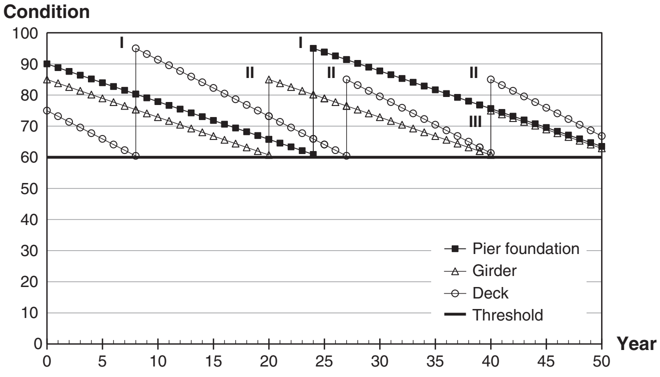


Fig. 3. Conditions of elements within the analysis period for the traditional model.

constraint logic programming, which embeds constraints into a logic program, and is a programming paradigm where relations between variables can be stated in the form of constraints [19–22]. Constraint programming has been widely and successfully applied to handle complex combinatorial problems in different fields, such as construction scheduling problems [23,24].

5.2. Model validation

A highway bridge with a high traffic volume is used to examine the model's capability. Three elements, pier foundations, girders and bridge deck, are considered for maintenance planning. The initial conditions of these three elements are 90, 85, and 75, respectively. The deterioration rates are set as 1.212, 1.212, and 1.818 per year, respectively [25]. Each element has three maintenance types (I, II, and III) to choose from. The effect, cost, and duration of each maintenance type of the three elements are shown in Table 1. The upper and lower bounds of the minimum acceptable condition range are set at 70, and 60, respectively (i.e., UB = 70, LB = 60). For comparison, the maintenance threshold (minimum acceptable condition) is assigned as 60 (i.e., UB = LB = 60).

The average traffic on this bridge is 28,700 vehicles/day. The analysis period is set at 50 years. The discount rate is assumed to be 0%. During maintenance, the traffic speed reduces from 100 km/h to 70 km/h because of partial lane closures [26]. Because the average salary of employees of the Taiwan area was NT$454,581/year and the annual working hours were 2040, the users' time value was NT$223/h [27]. The vehicle operation cost is NT$108/h [28,29]. The accident cost is assumed to be NT$23,557,000 per accident [30]. The normal accident rate is 1.9 per million-vehicle-km, and the accident rate during maintenance is 2 per million-vehicle-km [31].

The results obtained from both the traditional model and the concurrent maintenance model proposed in this study are presented for comparison. In the traditional model, with the maintenance threshold of 60 assigned, to reach the objective of the minimum life-cycle cost within the analysis period, the pier foundations will require a level-I maintenance in year 24, the girders will require level-II and level-III maintenance in years 20 and 40, respectively, and the deck will require a level-I and two level-II maintenance operations in years 8, 27, and 40, respectively, as shown in Fig. 2. The conditions of the three elements within the 50-year analysis period all remain above 60 to ensure the safety and serviceability of these elements, as shown in Fig. 3. The minimum life-cycle cost obtained is NT$6,633,954, as shown in Table 2. In the traditional model without considering the integration of maintenance schedules among elements, it is found that there may be two maintenance activities implemented in the same year resulting in two user impacts in that year.

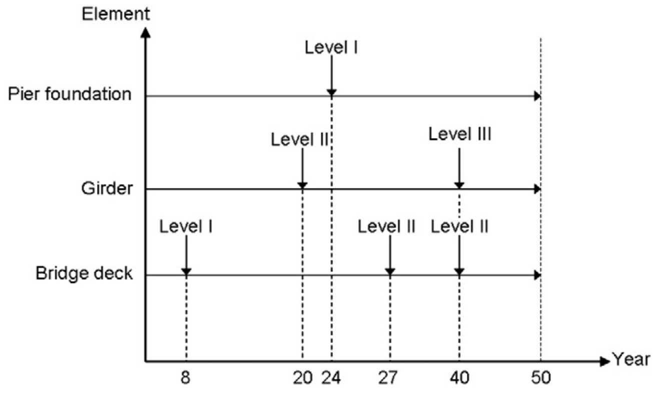


Fig. 2. Element maintenance plan for the traditional model.

The optimal maintenance plan obtained from the concurrent maintenance model is shown in Fig. 4. The maintenance timings for each element are adjusted to perform maintenance activities in the same year if possible. As shown in Fig. 4 and Table 3, three elements are scheduled for concurrent maintenance in years 20 and 39. The user cost for year 20 or 39 is then decided by the maintenance project with the longest duration among the three maintenance projects in that year. For example, as shown in Table 3, in year 20, a level-II maintenance with the duration of 36 days for the pier foundations, a level-II maintenance with the duration of 72 days for the girders, and a level-I maintenance with the duration of 73 days for the bridge deck will be performed. Therefore, the bridge lanes will be partially closed for 73 days to complete these three maintenance projects. The user cost for the 73 days of partial lane closures is NT$817,089. In year 39, the user cost is decided by the 65-day level-II maintenance project for the bridge deck; its duration is longer than the 32 days for the level-III maintenance project for the pier foundations or the 63 days for the level-III maintenance project for the girders. As shown in Fig. 5, the conditions of the three elements within the 50-year analysis period remain above 60 to ensure the safety and serviceability of these elements; however, to match the maintenance times, some early maintenance is planned for some elements. For example, the pier foundations and the deck undergo early maintenance in year 20, and

Table 2
Results for traditional model.

Element	Maintenance year	Level	Agency cost (NT$)	User cost (NT$)
Pier foundation	24	I	195,000	447,720
Girder	20	II	504,000	805,896
	40	III	444,000	705,159
Bridge deck	8	I	452,000	817,089
	27	II	404,000	727,545
	40	II	404,000	727,545
Subtotal			2,403,000	4,230,954
Total cost			6,633,954	

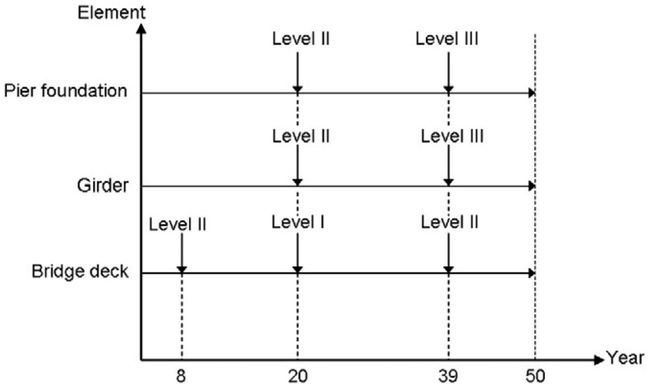


Fig. 4. Element maintenance plan for the concurrent maintenance model.

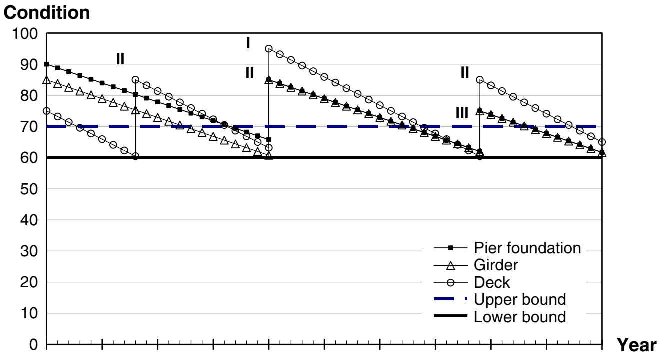


Fig. 5. Conditions of elements within the analysis period for the concurrent maintenance model.

early maintenance is also performed on the pier foundations and the girders in year 39.

From Figs. 2 and 4, it is observed that there are six maintenance time points (years 8, 20, 24, and 27 and two in year 40) in the traditional maintenance model, while there are only three maintenance time points (years 8, 20 and 39) in the concurrent maintenance model. Compared with the traditional model, within the analysis period of 50 years, the total user cost decreases by NT$1,958,775, and the total life-cycle cost reduces by NT$1,825,775. It is also observed that the number of maintenance activities of the proposed model is more than that of the traditional model. The former has seven maintenance activities, and the latter has six. It is found that in the concurrent maintenance model, to match the maintenance timings with other elements, maintenance activities with less effect may be chosen for elements and maintenance may be performed more often. Because the user costs incurred by maintenance activities are much greater than the agency costs of the maintenance activities, it is better to have some extra maintenance activity (if it can be scheduled at the same time as other elements) rather than to have one more maintenance time point causing greater user impact. The pier foundations are one example in the case studied. Therefore, it is also observed that the total agency cost increases by NT$133,000 to allow increased user cost savings of NT$1,958,775. We call the ratio of these two values the benefit–cost ratio (B/C); it is 14.73, as shown in Table 3.

5.3. Influence of discount rate on life-cycle cost

Sensitivity analysis of the discount rate ranging from 0% to 10% was conducted to study the influence of the discount rate on the life-cycle cost. As shown in Fig. 6, in the traditional model, the sensitivities of agency cost and user cost to discount rate are about the same because the numbers of these two costs are the same. Once there is an agency cost, a user cost is also incurred. The user cost is more than the agency cost in the traditional model no matter how the discount rate changes. In the proposed model, the agency cost is more sensitive to the discount rate than the user cost, as shown in Fig. 7. It is clear that the curve of agency cost crosses the curve of user cost at a discount rate of around 3%. The agency cost is greater than the user cost when the discount rate is smaller than 3.12%. When the discount rate is greater than 3.12%, the user cost is greater than the agency cost in the proposed model.

Table 3
Results for concurrent maintenance model.

Element	Maintenance year	Level	Agency cost (NT$)	User cost (NT$)
Pier foundation	20	II	174,000	(402,948)
	39	III	154,000	(358,176)
Girder	20	II	504,000	(805,896)
	39	III	444,000	(705,159)
Bridge deck	8	II	404,000	727,545
	20	I	452,000	817,089
	39	II	404,000	727,545
Subtotal			2,536,000	2,272,179
Total cost			4,808,179	
Costs compared with traditional model			+133,000	−1,958,775
B/C			14.73	

User costs within ( ) are not included in the summation for total cost because of concurrent maintenance.

Comparing these two models, the total life-cycle cost of the proposed model is less than that of the traditional model for the range of discount rates analyzed, as shown in Fig. 8. This is mainly because of the user cost. The maintenance planning obtained from the proposed model incurs much less user cost than the traditional model does, as shown in Fig. 9. However, in the case studied, the agency cost of the proposed model is more than that of the traditional model for the range of discount rates analyzed, as shown in Fig. 10. Comparing agency cost and user cost for the traditional model, the B/C ratio changes from 14.73 to 6.04 for the range of discount rates analyzed, as shown in Fig. 11, indicating the cost effectiveness of the proposed model.

6. Conclusion

The concept of concurrent element maintenance is proposed in this study. From the user point of view, the concept of concurrent maintenance tries to integrate maintenance timings of elements to reduce the impact of maintenance on road users. A concurrent maintenance model implementing the concept of concurrent maintenance and life-cycle cost is

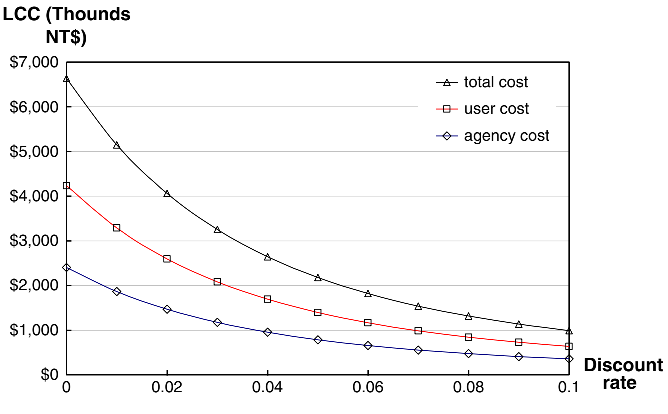


Fig. 6. Influence of discount rate on life-cycle cost (traditional model).

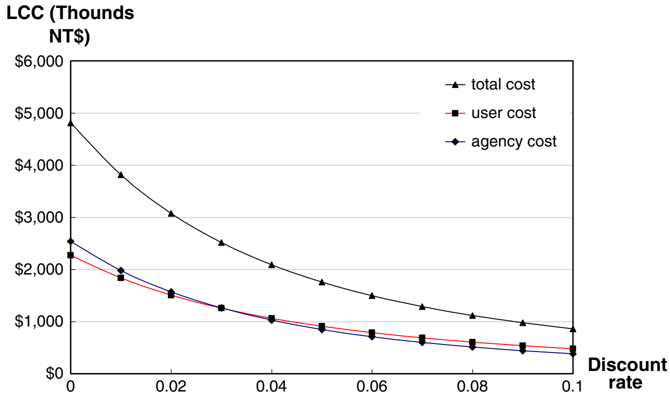


Fig. 7. Influence of discount rate on life-cycle cost (proposed model).

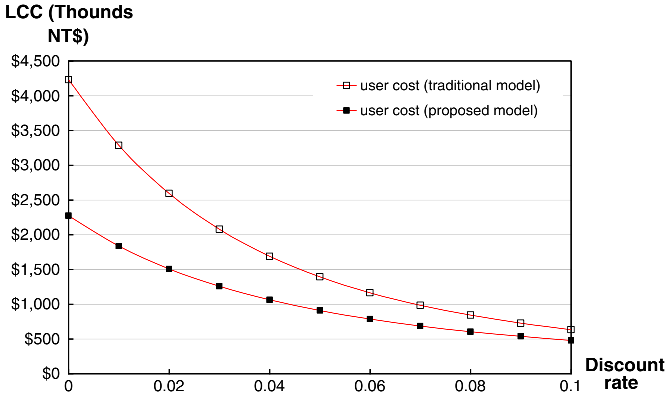


Fig. 9. Influence of discount rate on life-cycle user cost.

established with the objective of minimizing the life-cycle costs including agency costs and user costs of a bridge. It was found that compared with the traditional model, the maintenance time points, total user cost, and total life-cycle cost within the analysis period are reduced in the maintenance plan generated by the concurrent maintenance model. By managing the maintenance activities to achieve concurrent implementation, the impacts on road users of the maintenances are reduced. Although the agency cost obtained from the proposed model is more than that of the traditional model in the case studied, it allows for greater user cost savings. For the discount rates studied, 0% to 10%, the B/C ratios range from 14.73 to 6.04, indicating the cost effectiveness of the proposed model.

Interviews with experienced bridge maintenance experts confirm that the concept of element's concurrent maintenance can be implemented in practice. The proposed model could readily be incorporated into a comprehensive computer-based bridge management system. The model must be imported into the system; as well, the deterioration rates of bridge elements studied by other researches (e.g. [25]) must be imported or obtained from the system. The simplifying assumptions in the model can be relaxed in a computer-based bridge management system. For example, the deterioration rate of each element is assumed constant in the version of the model used here, while a bridge management system could incorporate deterioration rates that differ with an element's condition or with time, with appropriate changes to the equations for calculating the earliest and latest time of each maintenance (i.e., Eqs. (2), (3), (7) and (8)). Other information required for the proposed model can be obtained easily from agencies (such as upper and lower bounds of acceptable condition range, analysis period), official statistical records (such as discount rate, driver delay cost, vehicle operation cost, accident cost, average daily traffic), maintenance contractors (such as number of maintenance types, maintenance duration, cost, effect) and the bridge management system currently employed (such as the initial condition of each element, number of elements, and length of a bridge). The cost effect of detours is not considered in our work and should be studied further. The proposed concurrent maintenance model provides decision makers with another maintenance strategy from both agency and user points of view.

Acknowledgments

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Appendix A. Notation

The following symbols are used in this paper:

LCC	Life-cycle cost
C_t	Cost in year t
i	Discount rate
T	Analysis period
$ET_{j,k}$	Earliest time of the kth maintenance of element j
$LT_{j,k}$	Latest time of the kth maintenance of element j
IC_j	Initial condition of element j
UB	Upper bound of the minimum acceptable condition range
LB	Lower bound of the minimum acceptable condition range
r_j	Deterioration rate of element j

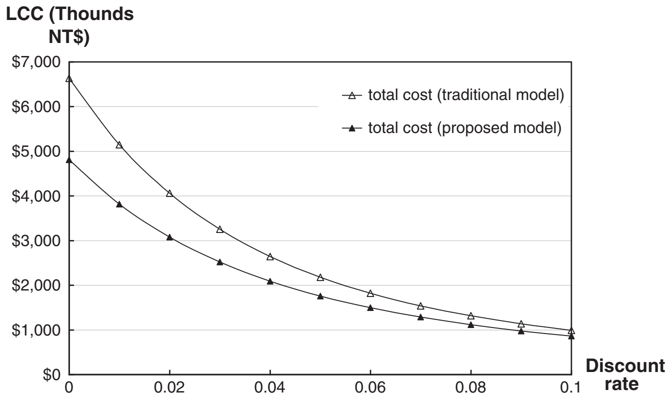

Fig. 8. Influence of discount rate on life-cycle total cost.

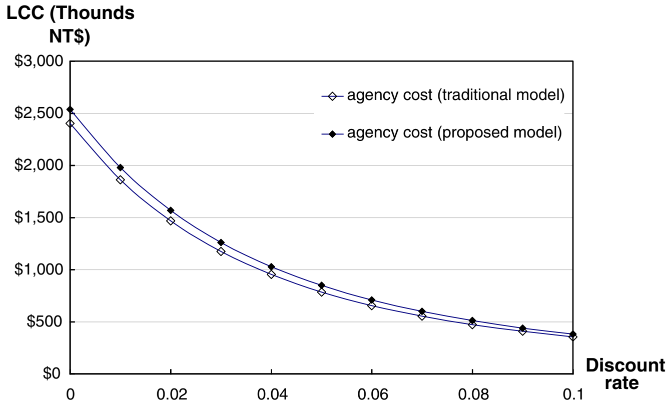

Fig. 10. Influence of discount rate on life-cycle agency cost.

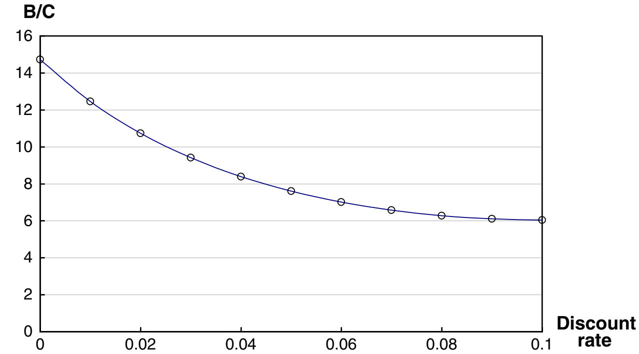

Fig. 11. Influence of discount rate on B/C.

$E_{j,k}$	Effect of the *k*th maintenance of element *j*
$Year_{j,k}$	Year of the *k*th maintenance performed of element *j*
$Work01_{j,t,m}$	Boolean variable with the value of 1 if the maintenance type *m* is performed for element *j* in year *t*
$Effect_{j,m}$	Maintenance effect of maintenance type *m* of element *j*
NM_j	Number of maintenance types of element *j*
N_j	Total number of maintenance operations performed for element *j*
$AC_{j,t}$	Agency cost of element *j* in year *t*
$MC_{j,m}$	Cost of maintenance type *m* of element *j*
$UC_{j,t}$	User cost of element *j* in year *t*
DOC	Driver delay cost per vehicle per day
VOC	Vehicle operation cost per vehicle per day
AC	Accident cost per vehicle per day
$traffic$	Traffic volume of the bridge
$D_{j,m}$	Duration of maintenance type *m* of element *j*
L	Length of the bridge
S_a	Traffic speed when maintenance performed
S_n	Normal traffic speed
R_p	Users' time value per hour
R_c	Vehicle operational cost per hour
A_a	Accident rate when maintenance performed
A_n	Normal accident rate
C_a	Accident cost
UC_t	User cost for year *t*
EN	The number of elements of a bridge

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