KSCE Journal of Civil Engineering (2017) 21(1):27-36
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DOI 10.1007/s12205-016-1175-0

Construction Management
pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

Annual Rehabilitation Costs Estimation for a Bridge Network

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Received March 2, 2015/Revised February 26, 2016/Accepted March 9, 2016/Published Online May 10, 2016

Abstract

The objective of this paper is to present an integrated multi-year rehabilitation planning model (IMRPM) for a bridge network. A multi-year capital program can provide an explicit, steady vision for financial and expenditure strategies as well as improve the efficiency of the allocation of limited resources. Estimating the precise annual rehabilitation needs for sound bridge management is essential to achieving the goals of a multi-year capital program; however, the current rehabilitation planning techniques tend to underestimate the annual rehabilitation costs by overlooking the potential rehabilitation needs which can arise by delaying of Maintenance/Repair (M/R) projects due to insufficient annual funding. The presented model integrates a multi-year rehabilitation capital program into an M/R program within the same multi-year period. The model engages a genetic algorithm for a project-level analysis process to identify M/R and rehabilitation projects over a defined multi-year analysis period (e.g., three, five, or ten years) for each M/R program and rehabilitation program. As a result of this process, the annual rehabilitation costs during a multi-year period initially can be estimated. Then, the initial annual rehabilitation costs can be finalized by including newly-identified rehabilitation needs, which are developed through the annual reanalysis process resulting from the delay of M/R projects in prior years. The annual reanalysis process considers the concept of time floats for M/R projects. The presented model is expected to be useful to efficiently control delayed M/R projects and to provide more reliable estimation for annual rehabilitation needs.

Keywords: *rehabilitation, multi-year planning, bridge management, time float, rehabilitation costs, annual cost estimation*

1. Introduction

Transportation agencies employ bridge management systems to determine rehabilitation needs by identifying the best maintenance, repair, and rehabilitation (MR&R) strategies which best address an agency's optimization goals (Tarighat and Miyamoto, 2009; Patidar *et al.*, 2007). In the context of MR&R strategies, maintenance can be defined as the activities considered for keeping a bridge in its current condition by preventing further deterioration (Russell, 2004). Repair is required to correct the damages that develop locally in structural members (Randomski, 2002). Rehabilitation includes the activities undertaken to address the cause of deterioration in the overall structure so that is effective to improve a bridge's current physical condition rating and its serviceability (Williamson, 2007).

Combined-level optimization models are widely used for bridge management systems to establish MR&R strategies after observing the limitations in the previous project- and network-level optimization models (Patidar *et al.*, 2007). The general structured methodology of the combined-level optimization models utilizes the following four steps to identify rehabilitation projects: 1) creating an inventory of bridges for rehabilitation, 2) assessing all bridges in the inventory to determine the intervention time for rehabilitation from the best MR&R alternative through an economic analysis, 3) prioritizing the rehabilitation projects by the consequent ratings at the network-level, and 4) determining a set of rehabilitation projects to be performed within an available annual budget over a multi-year analysis period (Boex *et al.*, 2000). Combined optimization models are generally established over a multi-year analysis period to develop a multi-year budgeting process which can provide federal, state, and local governments with potential benefits such as the following: 1) providing a more explicit and steady vision of bridge management goals (e.g., enhancing structural integrity, increasing serviceability, etc.), 2) enabling continuous evaluation of the annual budget in the context of the long-term bridge management goals, and 3) encouraging efficiency in the allocation of limited resources through the systematic review of expenditure priorities (Li *et al.*, 1998; Hegazy *et al.*, 2004).

Since bridge management programs always face the problem of insufficient investment compared to their actual MR&R needs, the current multi-year optimization models focus on the development of the methods to prioritize and select MR&R projects in preconstrained conditions such as the budget limitations or the level of performance. There are many previous studies which use this principle (e.g., Li *et al.*, 1998; Hegazy *et*

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al., 2004; Li *et al.*, 2010). Although these optimization models are useful in terms of efficient use of the limited funds for the MR&R projects, identifying the total MR&R for strategic financial planning is also needed.

Identification of the total MR&R needs does not simply indicate the annual costs that can be naturally estimated in the process of creating asset inventories for MR&R projects. The total MR&R needs should be informative to the bridge management planning process. For example, Tsai *et al.* (2004) estimated the amount of annual rehabilitation funding equally distributed among the Districts in the state of Georgia, and Yoon and Hastak (2012) introduced a multi-year optimization model to estimate a leveled annual rehabilitation requirement using the new concept of “rehabilitation time float.” The use of these models are applicable for sole multi-year rehabilitation planning, but not for multi-year rehabilitation planning in the context of MR&R strategies. That is, rehabilitation projects are generally considered for bridges that have reached conditions beyond Maintenance/Repair (M/R) activities (Neves and Frangopol, 2005). Unfortunately, many bridges suffer from limited funding, which eventually delays some of the timely M/R activities bridges need during a multi-year period. As a result, the conditions of deferred bridges continue to deteriorate beyond the minimal threshold for M/R and consequently require rehabilitation activities. Therefore, reliable multi-year rehabilitation planning should include the bridges which are expected not to be selected within the multi-year planning due to their lower priorities and the budget constraints of the M/R program. Otherwise, the rehabilitation capital planning process will provide underestimated annual rehabilitation needs from the unrealistic assumption that the annual funding is sufficient to cover all the M/R activities needed within the multi-year period.

The objective of this paper is to present an integrated multi-year rehabilitation planning model (IMRPM) to precisely estimate the annual rehabilitation needs for a bridge network, considering “newly-identified rehabilitation projects.” The newly-identified rehabilitation projects are those M/R projects that are not selected due to limited annual funding for a multi-year M/R program. The IMRPM employs a new principle, “annual reanalysis using time float,” to identify the new rehabilitation projects. The annual reanalysis is a recurring process to reprioritize the M/R projects in an integrated list (i.e., the originally identified M/R projects plus the M/R projects deferred from the previous fiscal years) for final selection for each fiscal year within a multi-year period. A time float is an acceptable time frame within which M/R projects can be delayed. Project-level analysis based on a genetic algorithm is utilized to identify M/R and rehabilitation projects over a defined multi-year analysis period. In particular, the project-level analysis estimates the time floats of the M/R projects for the annual reanalysis process during the multi-year period. While the IMRPM is presented for a bridge network, a case study to demonstrate the model considers concrete bridge decks specifically. The results show that the presented model can be efficiently utilized to control delayed M/R projects and to provide a reliable method to estimate annual rehabilitation needs.

2. Trigger Values for MR&R Activities

MR&R activities can be applied to the primary bridge elements (e.g., decks, superstructure, and substructures) based on time intervals, condition (or performance) threshold, or a combination of time and condition (Petcherdchoo *et al.*, 2008). Time-based activities have regular time intervals to apply while condition-based activities are applied when bridge elements reach a defined condition level. The combination of time- and condition-based activities considers a certain condition level for the initial application of MR&R activities, and then the subsequent applications are determined by the regular time intervals (Neves and Frangopol, 2005). The combination of time- and condition-based activities can be applied in reverse order according to the public agency’s approach. The details of the time-based and condition-based activities are discussed in the following subsections.

2.1 Condition Threshold Ratings for Application of MR&R Activities

State Departments of Transportation (DOTs) are required to submit National Bridge Inventory (NBI) inspection records, including the condition ratings of bridges, to the Federal Highway Administration (FHWA) every year. The FHWA publishes a guideline for the inspection of the primary elements of bridges based on condition rating codes which range from “9” to “0” (FHWA 1995). Condition rating code “9” denotes bridges in new condition, “1” for bridges needing to be closed to traffic, and “0” for bridges in failed condition. In the same guideline, a “6” or “7” suggests that minor repair or maintenance is required while a “4” or “5” suggests that major repair is needed. The bridge elements in a “4” condition require major repair urgently. Based on the guideline, many states develop and operate their own internal coding systems for their bridge systems. For example, Connecticut DOT (ConnDOT) suggests that minor and major maintenance are required for bridges with the condition ratings of “7” and “6,” respectively (ConnDOT, 2001). Bridge elements in a “5” or “4” condition potentially need minor rehabilitation and major rehabilitation, respectively. Bridge elements having a NBI condition rating of “4” require major rehabilitation immediately. Missouri DOT (MoDOT) has the same condition ratings to apply MR&R activities to bridge elements as ConnDOT, but their bridge elements with a rating of “8” might require minor preventive maintenance against hairline cracks (MoDOT, 2000). In addition, FHWA administers the Highway Bridge Replacement and Rehabilitation Program (HBRRP), which is the primary federal program for state funding to improve the condition of bridges in the NBI through replacement, rehabilitation, and systematic preventive maintenance. Structurally deficient bridge decks that have a NBI condition rating equal to or less than “4” are eligible for rehabilitation or replacement by HBRRP funding (FHWA, 2007).

2.2 Time Intervals for Application of MR&R Activities

New York State DOT (NYSDOT) is a representative state that has typical preventive maintenance procedures conducted on a scheduled interval basis. For example, bridge deck cleaning has a frequency of two years, crack sealing is completed every four years, and overlay replacement is every 12 years (NYSDOT, 2008). Virginia DOT (VDOT) also suggests time-based preventive maintenance activities for bridge elements. For example, concrete decks are washed every year and thin epoxy overlay and concrete overlay are scheduled for installation on bare concrete decks every 15 years and 30 years, respectively (Sprinkel *et al.*, 2006). Hong (2003) surveyed state DOTs in the U.S. to identify the timing of various MR&R activities for concrete bridge decks, (e.g., bridge cleaning, crack sealing, patching, concrete overlay, and replacing deck). The survey results show that many state DOTs also consider time-based activities with the condition threshold ratings for application of MR&R activities. However, the ages for First Application (FA) and the Frequencies Thereafter (FT) of the MR&R activities vary widely except for bridge cleaning. For example, Texas and Oklahoma are located in the southern climate region, and the FAs of patching are 30 and 20 years, respectively, while Alabama and Georgia in the southeast climate region consider FAs of patching at 30 and 15 years, respectively.

3. Prioritization for MR&R Projects at the Network-Level

The traditional prioritization approaches are based solely on the worst-condition first (Wang *et al.*, 2003). However, these approaches are not suitable when the purposes of the prioritization in a bridge management program are generally to allocate projects with insufficient funding as well as to improve the overall performance of bridges at the network-level (Liu and Frangopol, 2005). Therefore, prioritization approaches have evolved to utilizing tools that determine the cost-effective investments from a network viewpoint. In measuring cost-effectiveness, the "cost" generally implies the life-cycle cost which is the cost implications of MR&R activities during the lifetime of a bridge. Those costs can be classified as agency and user costs. Agency costs are incurred for direct MR&R activities by the agency while user costs are those experienced by bridge users, (e.g., travel time, motor vehicle operating costs, and accident costs) (American Association of State Highway and Transportation (AASHTO), 1993). On the other hand, "effectiveness" in the context of cost-effectiveness indicates the overall condition levels of facilities or functional values such as serviceability, reliability, or connectivity (Liu and Frangopol, 2005).

The prioritization parameters for cost-effectiveness can be expanded further to include various measures to reflect the functional, economic, social, environmental, and national safety impacts of facilities (Wang *et al.*, 2003). Gokey *et al.* (2009) identified the factors for prioritization from mainly two perspectives: maintenance and economic. The prioritization factors from the economic perspective include the current Average Daily Traffic (ADT) and projected future ADT as a measure to evaluate the area's surrounding economy as well as commuters' dependency on bridges. The lengths of detours are also included as a factor in order to estimate the economic ordinal ranking for possible inconvenience for commuters due to bridge closure. Sinha *et al.* (2010) developed the ranking criteria for the Indiana Bridge Management System (IBMS), which consist of the economic, condition, bridge safety, and community impact indicators in order to compute the disutility value of a bridge. The authors concluded that the disutility value represents the level of criticality of the bridge requiring MR&R activities. Each criterion utilizes the following evaluation factors:

- Economic disutility: agency and user costs
- Condition disutility: structural condition, remaining service life, and wearing surface
- Bridge safety disutility: functional integrity and inventory rating
- Community impact disutility: detour length

Yoon (2012) developed a Total Prioritization Scale (TPS) for concrete bridge decks. The TPS is a composite scale of the three different aspects of performance, economics, and criticality. The performance aspect considers the physical condition of a concrete bridge deck. The economics aspect considers the economic efficiency by measuring the increase in the average annual condition level per the unit equivalent uniform annual cost. Lastly, the criticality aspect measures the impact level of the failure of concrete bridge decks. This aspect is derived from the AASHTO criteria to protect the nation's critical mobility assets from terrorism (Ham and Lockwood, 2002). The ADTs and the detour lengths for concrete bridge deck projects are the main parameters considered for this aspect. The three aspects have different unit values. Therefore, the TPS is computed by multiplying the normalized scales of the three aspects by their important weights.

4. Development of IMRPM

The IMRPM consists of two modules: Module-1 performs the development of candidates for both maintenance/repair (M/R) and rehabilitation projects, and Module-2 conducts the reanalysis process to finally identify rehabilitation projects within a planned multi-year period. Fig. 1 is the flowchart for the development of two inventories for M/R and rehabilitation projects and the annual reanalysis process.

4.1 Module-1: Inventories for MR&R Projects

To identify the best MR&R strategies for individual bridges, Module-1 first applies a project-level optimization model to generate multiple alternatives consisted of MR&R projects during the lifetime. Then, the alternatives which best address an objective goal and constraints are selected for the individual bridges. Once the best MR&R alternatives for the bridges are identified, Module-1 creates two independent inventories for M/R

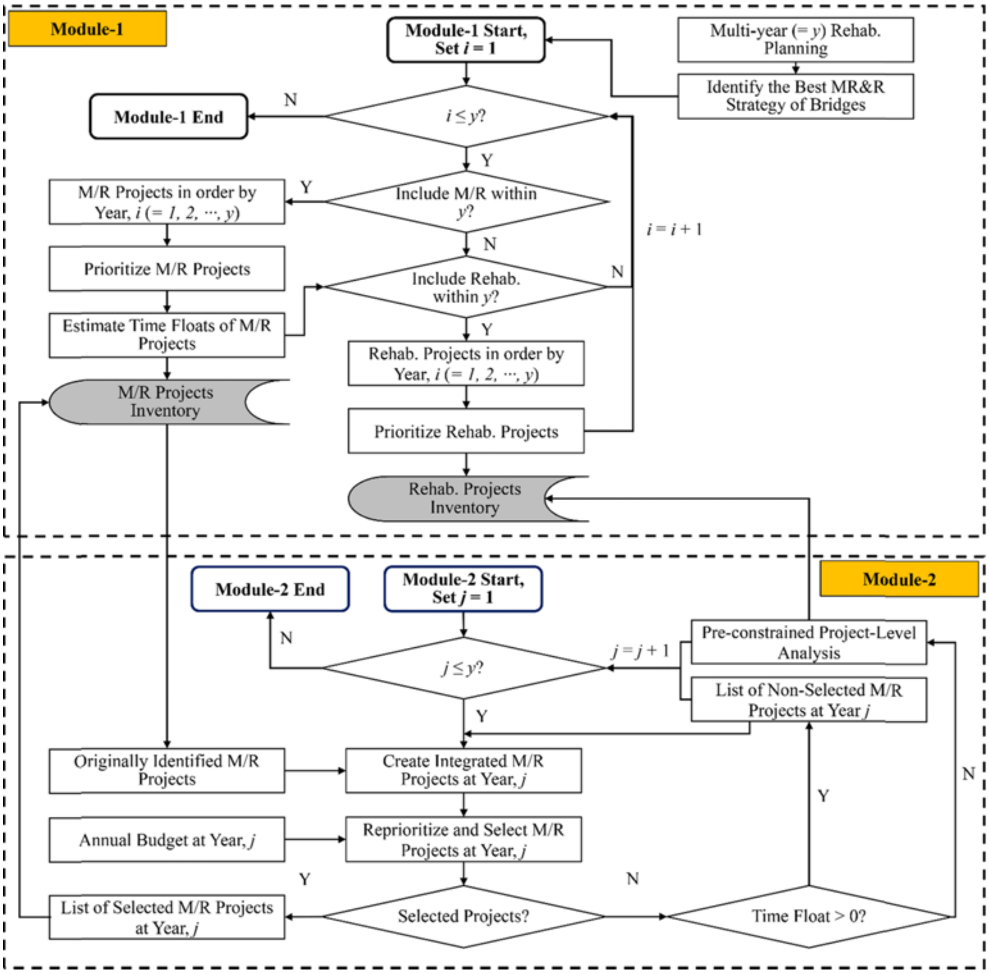


Fig. 1. Flowchart for the IMRPM

and rehabilitation projects by taking a series of processes such as collecting and prioritizing the MR&R projects scheduled within a planned multi-year analysis period (= y) as well as storing them in two separate databases. The database for M/R projects particularly requires the time floats of all M/R projects.

The prioritization approach in Module-1 employs a cost-effectiveness measure. In the context of cost-effectiveness here, the cost represents the present value of the MR&R activities and the effectiveness is the improvement of the average condition level over the analysis period. The following Eqs. (1) and (2) estimate the cost and effectiveness measures. The cost measure is a sum of the present costs of MR&R activities so the present value formula in economics is restated as follows:

$$C_{PV,B} = C_{FV,B} \times \left[\frac{1}{(1+d)^t}\right] \tag{1}$$

where, $C_{FV,B}$ is the future value of a maintenance, repair, or rehabilitation activity at year t, and $C_{PV,B}$ is the present value of $C_{FV,B}$ converted by a discount rate, d. The equation for the effectiveness (= E_B) of a bridge (= B), which is derived from the study (Labi *et al.*, 2006) to estimate the long-term treatment effectiveness of microsurfacing applications, is:

$$E_B = \frac{Ave.(CL')_B - Ave.(CL)_B}{Ave.(CL)_B} \tag{2}$$

where, $Ave.(CL')_B$ is the average of the annual condition ratings increased due to implementation of MR&R activities during the multi-year analysis period, and $Ave.(CL)_B$ is the average of the annual condition ratings without any MR&R activities. Therefore, the priorities of MR&R projects are determined by the following formula:

$$CE = \frac{E_B}{C_{PV,B}} \tag{3}$$

It is implied in the formula that bridges are deemed to have higher priority when the implementation of MR&R activities achieves greater improvement of their average condition levels with lower MR&R costs.

A time float is an acceptable time frame within which maintenance/repair projects can be delayed. It can be determined using either time intervals, condition ratings, or both. As the NBI coding system is commonly used to evaluate the physical conditions of bridge elements by many state DOTs, condition-based trigger values are defined for MR&R activities as shown

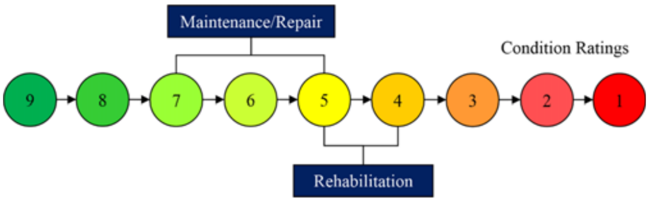


Fig. 2. Trigger Values for MR&R Activities

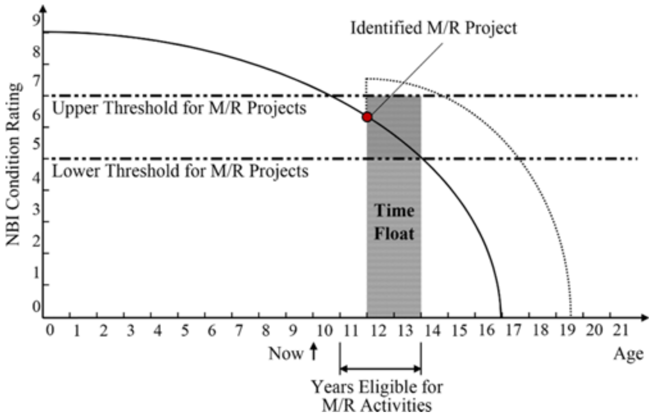


Fig. 3. Hypothetical Example to Estimate Time Float

in Fig. 2. According to the trigger values in Fig. 2, the bridge elements having ratings of “7” to “5” are candidates for maintenance/repair activities. However, it should be noted that the actual condition of a bridge implies continuous values at discrete time horizons although the condition is rated as discrete values. Such a rule is also applied for the rehabilitation activities. Therefore, the upper and lower threshold values for MR&R projects in Fig. 2 can be interpreted as follows:

- 5 ≤ bridge elements < 7: maintenance and repair activities
- 4 ≤ bridge elements < 5: rehabilitation activities

The time floats of M/R projects can be estimated based on the defined trigger values. Fig. 3 shows a hypothetical example to explain the process of estimating the time floats for individual bridges. First, suppose that a bridge deteriorates following the solid curve in the figure, which represents the deterioration pattern when there are no MR&R activities. Also, suppose that the project-level analysis for the bridge identifies the best MR&R strategy and suggests one M/R project at Year 12 as described in Fig. 3. The example assumes that a decision-maker is planning a five-year capital program (i.e., Years 11-15) at the base year, Year 10. According to the defined upper and lower threshold values, it is expected that the condition level of the bridge will go below the upper threshold at Year 11 and stay in the boundary for M/R activities until Year 14, which implies that the bridge can be delayed until Year 14 to be considered as an M/R project. If the bridge would not be selected even for the M/R project at Year 14 due to insufficient funding, it should be considered as a rehabilitation candidate for Year 15. Therefore, one can say that the bridge has a time float of (+2) for the M/R project.

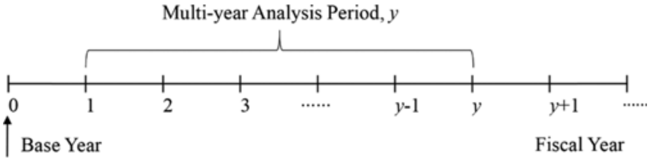


Fig. 4. Multi-year Analysis Period for Rehabilitation Planning

4.2 Module-2: Reanalysis Process for Final List of Rehabilitation Projects

The annual reanalysis process (Module-2) is designed to identify the final list of rehabilitation projects by taking the steps described in Fig. 1. The annual reanalysis process is repetitive at each fiscal year within a defined multi-year analysis period. For example, as shown in Fig. 4, when a y-year analysis period is set up at the base year, the annual reanalysis process repeats the steps of Module-2 from Year 0 to Year y. The first step of the process is to retrieve the M/R projects which have already been prioritized by Module-1 at any single year j at the base year. Also, the process checks the presence of the M/R projects delayed from Year j-1. Then, the two groups of M/R projects are reprioritized by the updated prioritization scales of the delayed M/R projects and selected considering an annual available budget for Year j. The list of selected bridges goes back to the database while the non-selected bridges are reviewed for the existence of remaining time floats. If the non-selected bridges have remaining time floats for M/R projects, they move to the waiting list to be reanalyzed at the following fiscal year, j+1. Otherwise, the non-selected bridges need a project-level analysis to reidentify the best MR&R strategies in the pre-constrained condition, which assigns no MR&R projects for Years 1 to y-1. Finally, the bridges with newly-identified rehabilitation projects within the multi-year analysis period y are stored in the rehabilitation projects inventory, and their rehabilitation costs are estimated and added to the original annual rehabilitation needs.

5. Application of IMRPM

To test the model, a case study consisting of 119 concrete bridge decks on interstate highways in the state of Indiana was conducted. As the focus of this paper is to demonstrate the model, which is designed to estimate annual rehabilitation costs within a multi-year analysis period including newly-identified rehabilitation projects from delayed M/R projects, some of the essential parameters were assumed in order to simplify the application process but at a level that would not affect the result. These assumptions included the following: the annual deterioration rate is constant at -0.17/year, which is an average annual rate that the bridges in the state of Indiana deteriorate; the best MR&R strategy is determined by considering the lowest agency life-cycle cost; the MR&R activities include crack sealing, full-depth patching, and asphalt overlay as they are prevalent treatment techniques to control cracking and spalling on concrete bridge decks; the condition of a concrete bridge deck is evaluated by the cracking and spalling areas suggested by the INDOT coding guide; and, the life-cycle cost applies a real discount rate with constant dollars.

A Genetic Algorithm (GA) was utilized to generate the alternatives of MR&R projects which are scheduled at discrete years during the service life of a concrete bridge deck at the project-level. GA is well-known as a heuristic search-and-optimization method suitable for discrete and combinatorial problems which cannot be solved in reasonable times (Aarts and Lenstra, 1997; Marinakis and Marinaki, 2010). The GA tool used for the application of IMRPM was Evolver 5.7 which is add-in to Microsoft Excel. Evolver was configured by the parameters such as a population size and crossover and mutation rates. The parameter setting determined through the preliminary tests with different values of the parameters were 100 for the population size, 0.6 for the crossover rate, and 0.1 for the mutation rate. Also, the number of trials to identify the optimal MR&R strategy was set to 2,500. When Evolver was requested to search for the best MR&R alternative in the given GA system, it encoded the integer values of 0-3 to 100 cells to generate feasible alternatives consisted of MR&R activities (e.g., do-nothing: 0, maintenance: 1, repair: 2, and rehabilitation: 3). The fitness values (i.e., life-cycle costs for the application of IMRPM) of the feasible alternatives were compared for the purpose of selecting two alternatives with higher fitness values from the current population. Then, the selected alternatives were used to generate offspring for the next trial. Finally, Evolver identified one best alternative of MR&R projects at the project-level analysis.

Table 1 shows the result of the identified M/R projects within the five-year analysis period FY 2015-2019. The costs of the M/R projects at each year are the present values estimated by a discount rate of 3.8%. Most of the smaller costs (less than or around $1,000) were estimated for the maintenance activity "crack sealing." In particular, Table 1 includes the time floats, which have a key role in the annual reanalysis process. "N/A" (not applicable) is shown in some cases because the conditions of the bridges stay in the M/R area within the multi-year analysis period despite the delays. The numbers represent the maximum years that the bridges can be considered M/R projects. For example, concrete bridge deck 33980 should be included in Year 2015 or Year 2016 for its M/R project; otherwise, it becomes a rehabilitation project candidate for Year 2017 because its time float is "1".

In Table 1, the M/R projects in each year are prioritized based on their cost-effectiveness estimated by Eq. (3). As a result, Table 2 contains a prioritized list of the M/R projects and the initial selection (i.e., shaded areas) of the M/R projects within a constant M/R budget of $80,000/year. The annual budget was assumed to be roughly 50% of the average annual M/R needs ($160,000) because there is generally a funding gap of almost

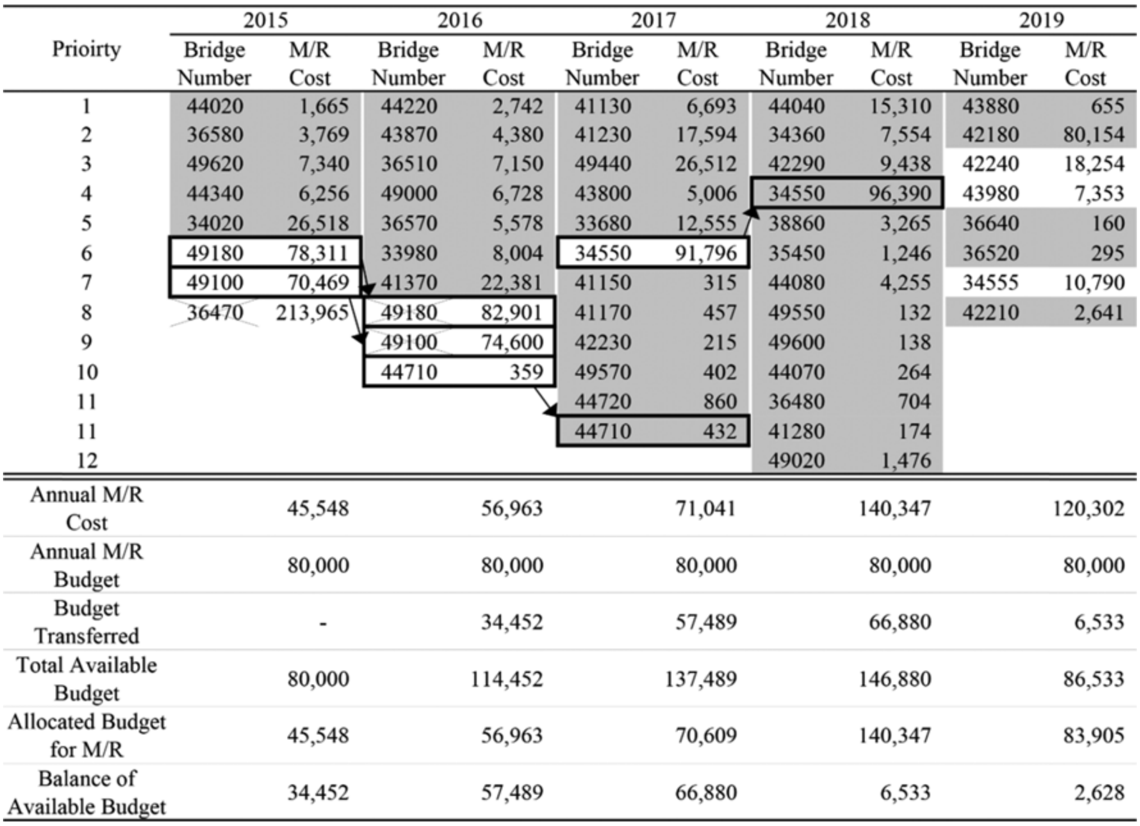
Table 1. Identified M/R Projects During FY 2015-2019

Bridge Number	Analysis Year for M/R Projects					TF	Bridge Number	Analysis Year for M/R Projects					TF
	2015	2016	2017	2018	2019			2015	2016	2017	2018	2019	
	M/R Cost ($)							M/R Cost ($)					
33680	-	-	12,555	-	-	N/A	42240	-	-	-	-	18,254	N/A
33980	-	8,004	-	-	-	1	42290	-	-	-	9,438	-	N/A
34020	26,518	-	-	-	-	1	43800	-	-	5,006	-	-	N/A
34360	-	-	-	7,554	-	N/A	43870	-	4,380	-	-	-	0
34550	-	-	91,796	-	-	1	43880	-	-	-	-	655	N/A
34555	-	-	-	-	10,790	N/A	43980	-	-	-	-	7,353	N/A
35450	-	-	-	1,246	-	N/A	44020	1,665	-	-	-	-	0
36470	213,965	-	-	-	-	0	44040	-	-	-	15,310	-	N/A
36480	-	-	-	704	-	N/A	44070	-	-	-	264	-	N/A
36510	-	7,150	-	-	-	0	44080	-	-	-	4,255	-	N/A
36520	-	-	-	-	295	N/A	44220	-	2,742	-	-	-	0
36570	-	5,578	-	-	-	2	44340	6,256	-	-	-	-	2
36580	3,769	-	-	-	-	2	44710	-	359	-	-	-	N/A
36640	-	-	-	-	160	N/A	44720	-	-	860	-	-	N/A
38860	-	-	-	3,265	-	N/A	49000	-	6,728	-	-	-	1
41130	-	-	6,693	-	-	0	49020	-	-	-	1,476	-	N/A
41150	-	-	315	-	-	N/A	49100	70,469	-	-	-	-	1
41170	-	-	457	-	-	N/A	49180	78,311	-	-	-	-	1
41230	-	-	17,594	-	-	1	49440	-	-	26,512	-	-	0
41280	-	-	-	174	-	N/A	49550	-	-	-	132	-	N/A
41370	-	22,381	-	-	-	1	49570	-	-	402	-	-	N/A
42180	-	-	-	-	80,154	0	49600	-	-	-	138	-	N/A
42210	-	-	-	-	2,641	N/A	49620	7,340	-	-	-	-	0
42230	-	-	215	-	-	N/A	Total	408,293	57,322	162,405	43,957	120,302	

Table 2. M/R Projects Initially Prioritized and Selected

Priority	2015		2016		2017		2018		2019	
	Bridge Number	M/R Cost	Bridge Number	M/R Cost	Bridge Number	M/R Cost	Bridge Number	M/R Cost	Bridge Number	M/R Cost
1	44020	1,665	44220	2,742	41130	6,693	44040	15,310	43880	655
2	36580	3,769	43870	4,380	41230	17,594	34360	7,554	42180	80,154
3	49620	7,340	36510	7,150	49440	26,512	42290	9,438	42240	18,254
4	44340	6,256	49000	6,728	43800	5,006	38860	3,265	43980	7,353
5	34020	26,518	36570	5,578	33680	12,555	35450	1,246	36640	160
6	49180	78,311	33980	8,004	34550	91,796	44080	4,255	36520	295
7	49100	70,469	41370	22,381	41150	315	49550	132	34555	10,790
8	36470	213,965	44710	359	41170	457	49600	138	42210	2,641
9					42230	215	44070	264		
10					49570	402	36480	704		
11					44720	860	41280	174		
12							49020	1,476		
Annual M/R Cost		408,293		57,322		162,405		43,957		120,302
Annual M/R Budget		80,000		80,000		80,000		80,000		80,000
Budget Transferred		-		34,452		57,130		66,521		102,564
Total Available Budget		80,000		114,452		137,130		146,521		182,564
Allocated Budget for M/R		45,548		57,322		70,609		43,957		120,302
Balance of Available Budget		34,452		57,130		66,521		102,564		62,262

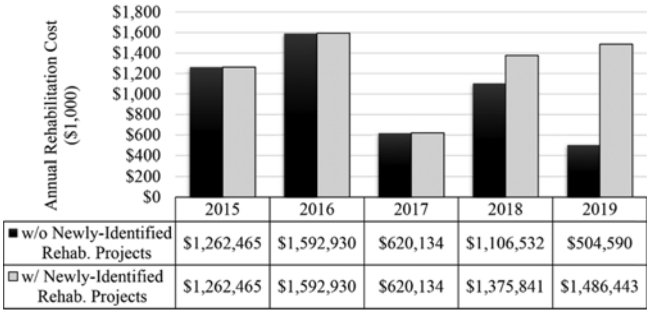
Table 3 The Results of the Annual Reanalysis Process



Prioirty	2015		2016		2017		2018		2019	
	Bridge Number	M/R Cost	Bridge Number	M/R Cost	Bridge Number	M/R Cost	Bridge Number	M/R Cost	Bridge Number	M/R Cost
1	44020	1,665	44220	2,742	41130	6,693	44040	15,310	43880	655
2	36580	3,769	43870	4,380	41230	17,594	34360	7,554	42180	80,154
3	49620	7,340	36510	7,150	49440	26,512	42290	9,438	42240	18,254
4	44340	6,256	49000	6,728	43800	5,006	34550	96,390	43980	7,353
5	34020	26,518	36570	5,578	33680	12,555	38860	3,265	36640	160
6	49180	78,311	33980	8,004	34550	91,796	35450	1,246	36520	295
7	49100	70,469	41370	22,381	41150	315	44080	4,255	34555	10,790
8	36470	213,965	49180	82,901	41170	457	49550	132	42210	2,641
9			49100	74,600	42230	215	49600	138		
10			44710	359	49570	402	44070	264		
11					44720	860	36480	704		
11					44710	432	41280	174		
12							49020	1,476		
Annual M/R Cost		45,548		56,963		71,041		140,347		120,302
Annual M/R Budget		80,000		80,000		80,000		80,000		80,000
Budget Transferred		-		34,452		57,489		66,880		6,533
Total Available Budget		80,000		114,452		137,489		146,880		86,533
Allocated Budget for M/R		45,548		56,963		70,609		140,347		83,905
Balance of Available Budget		34,452		57,489		66,880		6,533		2,628

50% under the total needs for surface transportation to maintain a state of good repair (American Society of Civil Engineers, 2013). The initial selection process also considered the budget transfer of the balance from the previous years. For example, the balance after allocating the available budget to the selection of the M/R projects in Year 2015 is $34,452 (= $80,000 - $45,548), and the balance was transferred to Year 2016 so that the total available budget is $114,452 (= $80,000 + $34,452).

As shown in Table 2, there were originally four M/R projects which were not selected due to the annual limit of the total available budget. The non-selected M/R projects then were reconsidered for the annual reanalysis process at the later fiscal years within their time floats. Bridges 49180, 49100, 36470, and 34550 had time floats of "1," "1," "0," and "1" respectively as estimated in Table 1, which implies that bridge 36470 should be removed from this multi-year M/R program when the annual reanalysis for Year 2016 is considered at the base year, Year 2014. The bridge should be moved to the rehabilitation program instead. According to the flowchart for Module-2, a pre-constrained project-level analysis was conducted to find the new best MR&R strategy, which finally identified a new rehabilitation project at Year 2019 with the rehabilitation cost of $981,853. Since this rehabilitation project is in the current five-year analysis period, it was added to the annual rehabilitation needs for Year 2019. On the other hand, bridges 49180 and 49100 were moved to Year 2016 and reprioritized with other M/R projects in Year 2016, which were previously screened through the Module-1 process. As a result, new priorities for the updated list of M/R projects were arranged as displayed in Year 2016 in Table 3. Compared to the prioritized M/R projects for Year 2016 in Table 2, the only change in priorities was that bridge 44710 is followed by the delayed bridges. The total available budget of $114,452 was applied for the final selection of the M/R projects for Year 2016, and the result shows that three M/R projects (bridges 49180, 49100, and 44710) were not selected. Bridges 49180 and 49100 have no time floats to move to Year 2017 as they were from Year 2015 so they were removed from the M/R program like bridge 36470. The pre-constrained project-level analysis for bridges 49180 and 49100 identified new rehabilitation projects at Years 2021 and 2018, respectively. Since bridge 49100 required a rehabilitation project at a cost of $269,309, it also was added to the annual rehabilitation needs for Year 2018. The annual reanalysis process was recurrently conducted for Year 2017, 2018, and 2019 at the base year, and the final results are shown in Table 3.



	2015	2016	2017	2018	2019
■ w/o Newly-Identified Rehab. Projects	$1,262,465	$1,592,930	$620,134	$1,106,532	$504,590
□ w/ Newly-Identified Rehab. Projects	$1,262,465	$1,592,930	$620,134	$1,375,841	$1,486,443

Fig. 5. Annual Rehabilitation Costs between FY 2015-2019

6. Discussions of the Application Results

The Integrated Multi-year Rehabilitation Planning Model (IMRPM) presented in this paper contributes to the enhancement of current bridge management planning with two critical findings. First, this study suggests a method to control M/R projects which might not be selected at their originally planned years due to insufficient annual funding. The most challenging part of infrastructure management, including a bridge system, is a shortfall of investment in the constructed facilities compared to the needs required for maintaining them in a good condition. This funding problem has led many infrastructure management-related studies to focus on the development of optimization models for the cost-effective use of the limited resources. There also have been research activities which focused on reducing the funding gaps between the future investment needs and the actual budget capability for spending by developing various financing strategies. The purposes of all these efforts are to maximize the effects (or benefits) of the allocation of scarce resource and/or to address the investment needs in order to include more M/R projects. It is unavoidable, however, to delay some of the M/R needs and methods therefore are needed to efficiently handle the delayed needs. The proposed model, IMRPM, takes an initial step to addressing the chronic problem of delaying M/R needs using the concept of "time float." The IMRPM goes beyond current multi-year capital investment planning processes that update the M/R needs annually in that it provides a more informative list of the M/R projects projected for a multi-year period at a base year.

Second, the IMRPM enables transportation agencies to estimate more reliable annual rehabilitation needs during a multi-year analysis period under a given available funding constraint. Fig. 5 shows the annual rehabilitation needs results from the case study. The black color bars represent the annual rehabilitation costs without the consideration of newly-identified rehabilitation projects, which are typically adopted to estimate their annual rehabilitation costs. On the other hand, the gray color bars indicate the annual rehabilitation costs including the newly-identified rehabilitation projects, which were removed from the multi-year M/R program. In this example, the newly-identified rehabilitation projects are bridge 36470 with the rehabilitation cost of $981,853 at Year 2019 and bridge 49100 with the rehabilitation cost of $269,309 at Year 2018. The two sets of annual rehabilitation costs show no changes in the annual rehabilitation needs for the first three years, but the needs for the last two years are increased by the newly-identified rehabilitation projects. This result implies that the gaps between the annual rehabilitation costs with and without the newly-identified rehabilitation projects increase at the later years within a multi-year period as a growing number of M/R projects are delayed and finally go beyond the minimum threshold for maintenance and repair. The ability to precisely project future needs can affect the efficacy of a multi-year budgeting process. The IMRPM affirms that the financial planning for a multi-year rehabilitation program can be established based on the annual rehabilitation costs including all possible rehabilitation needs. Otherwise, the expected benefits by applying the multi-year budgeting process is likely to be reduced to financial planning based on the underestimated rehabilitation needs.

7. Conclusions

The ideal bridge management program is achieved when all the bridges in a network are controlled in a timely manner with the minimal use of available resources. The reality of funding shortfalls, however, makes it difficult to address all of the bridge M/R needs at their originally identified intervention years. There have been many efforts to solve this challenge to building reliable bridge networks. This paper presented an integrated multi-year rehabilitation planning model that is a significant expansion to the current efforts. The presented model demonstrated the annual reanalysis process to accommodate the M/R projects which expect to be delayed due to limited funding at the planning stage for a multi-year capital program. The impact of delayed M/R projects on the annual rehabilitation needs was also shown, building the groundwork for strategic financial planning. The findings of this paper are valuable in terms of enriching the current practice to establish reliable bridge management strategies.

The developed model needs further work to reinforce the contributions. First, the flowcharts of the integrated model should be expanded to include other feasible options, such as reconstruction and replacement, as the model is designed for the M/R and rehabilitation options only. Second, the demonstration of the model considered a single M/R activity for individual bridges within a multi-year period although it might be possible that bridges require multiple M/R activities with the period so the delay of a precedent M/R project could affect a succeeding M/R project. Lastly, the model requires the development of software to encompass the various computation demands such as prioritization, time floats, reanalysis and reprioritization, and selection of projects.

References

Aarts, E. H. L. and Lenstra, J. K. (1997). *Local search in combinatorial optimization*, Wiley, Chichester; New York, N.Y.

American Association of State Highway and Transportation Officcials (1993). *Guidelines for Bridge Management Systems*, Washington, D.C.

American Society of Civil Engineers (2013). *Report card for america's infrastructure,* American Society of Civil Engineers, Washington, D.C.

Boex, L. F. J., Martinez-Vazquez, J., and McNab, R. M. (2000). "Multi-year budgeting: A review of international practices and lessons for developing and transitional economies." *Public Budgeting & Finance*, Vol. 20, No. 2, pp. 91-112, DOI: 10.1111/0275-1100.00013.

Connecticut Department of Transportation (2001). *Bridge Inspection Manual,* www.ct.gov/dot/lib/dot/documents/dpublications/Inspection_Manual_061905.pdf. (Accessed November 21, 2014).

Federal Highway Administration (1995). *Recording and coding guide for the structure inventory and appraisal of the nation's bridges*, Report No. FHWA-PD-96-001, Washington, D.C.

Federal Highway Administration (2007). *Rehabilitation and replacement of bridge decks*, www.fhwa.dot.gov/bridge/071101.cfm. (Accessed May 18, 2014).

Gokey, J., Klein, N., Mackey, C., Santos, J., Pillutla, A., and Tucker, S. (2009). "Development a prioritization methodology for maintaining georgia's bridge infrastructure systems." *Proc., Systems and Information Engineering Design Symposium 2009*, Atlanta, GA, pp. 252-257.

Ham, D. and Lockwood, S. (2002). *National needs assessment for ensuring transportation infrastructure security*, American Association of State Highway and Transportation Officials, Washington, D.C.

Hegazy, T., Elbeltagi, E., and El-Behairy, H. (2004). "Bridge deck management system with integrated life cycle cost optimization." *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1866, pp. 44-50, DOI: 10.3141/1866-06.

Hong, T. (2003). *Evaluation of maintenance. repair, and rehabilitation (MR&R) strategy in concrete bridge deck,* Master Thesis, Purdue University, West Lafayette, IN.

Labi, S., Hwee, K. S., Lamptey, G., and Nunoo, C. (2006). "Long-term benefits of microsurfacing applications in Indiana-methodology and case study." *Proceedings of the 85th Annual Meeting of the Transportation Research Board*, Washington, DC.

Li, N., Haas, R., and Huot, M. (1998). "Integer programming of maintenance and rehabilitation treatments for pavement networks." *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1629, pp. 242-248, DOI: 10.3141/1629-27.

Li, Z., Madanu, S., Zhou, B., Wang, Y., and Abbas, M. (2010). "A heuristic approach for selecting highway investment alternatives." *Computer-Aided Civil and Infrastructure Engineering*, Vol. 25, No. 6, pp. 427-439, DOI: 10.1111/j.1467-8667.2010.00653.x.

Liu, M. and Frangopol, D. (2005). "Maintenance planning of deteriorating bridges by using multiobjective optimization." *Transportation Research Record: Journal of the Transportation Research Board,* CD 11-S, pp. 491-500.

Marinakis, Y. and Marinaki, M. (2010). "A hybrid genetic–Particle Swarm Optimization Algorithm for the vehicle routing problem." *Expert Systems with Applications*, Vol. 37, No. 2, pp. 1446-1455.

Missouri Department of Transportation (2000). *Critical inspection findings missouri bridge and culvert rating guidelines figures*, <http://www.modot.org/business/manuals/documents/bridgesection_2.pdf>. (Accessed February 27, 2015).

Neves, L. C. and Frangopol, D. M. (2005). "Condition, safety and cost profiles for deteriorating structures with emphasis on bridges." *Reliability Engineering and System Safety*, Vol. 89, No. 2, pp. 185-198, DOI: 10.1016/j.ress.2004.08.018.

New York State Department of Transportation (2008). *Fundamental of Bridge Maintenance and Inspection*, Albany, NY.

Patidar, V., Labi, S., Sinha, K. C., and Thompson, P. (2007). *Multi-objective optimization for bridge management systems*, NCHRP Report 590, Transportation Research Board, Washington, D.C.

Petcherdchoo, A., Neves, L. A. C., and Frangopol, D. M. (2008). "Optimizing lifetime condition and reliability of deteriorating structures with emphasis on bridges." *Journal of Structural Engineering,* Vol. 134, No. 4, pp. 544-552, DOI: 10.1061/(ASCE)0733-9445 (2008)134:4(544).

Radomski, W. (2002). *Bridge rehabilitation*, Imperial College Press, London.

Russell, H. G. (2004). *Concrete bridge deck performance*, *NCHRP Synthesis Report 333*, Transportation Research Board, Washington, D.C.

Sinha, K., Labi, S., McCullouch, B., Bhargava, A., and Bai, Q. (2010). *Updating and enhancing the indiana bridge management system (IBMS). FHWA/IN/JTRP-2008/30,* Joint Transportation Research

Program, Indiana Department of Transportation and Purdue University, West Lafayette, IN.

Sprinkel, M., Brown, M., and Thompson, P. (2006). *Preventative maintenance for concrete bridge decks,* Presented at 2006 Virginia Concrete Conference, Richmond, VA.

Tarighat, A. and Miyamoto, A. (2009). "Fuzzy concrete bridge deck condition rating method for practical bridge management system." *Expert Systems with Applications*, Vol. 36, No. 10, pp. 12077-12085, DOI: 10.1016/j.eswa.2009.04.043.

Tsai, Y., Gao, B., and Lai, J. (2004). "Multi-year pavement-rehabilitation planning enabled by geographic information system: Network analyses linked to Projects." *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 1889, pp. 21-30, DOI: 10.3141/1889-03.

Wang, F., Zhang, Z., and Machemehl, R. (2003). "Decision-making problem for managing pavement maintenance and rehabilitation Projects." *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 1853, pp. 21-28, DOI: 10.3141/1853-03.

Williamson, G. (2007). *Service life modeling of virginia bridge decks,* PhD Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Yoon, Y. and Hastak, M. (2012). "Multiyear infrastructure rehabilitation strategy within the context of MR&R." *Proc., Third International Symposium on Life-Cycle Civil Engineering: Life-Cycle and Sustainability of Civil Infrastructure Systems*, Vienna, Austria, pp. 1203-1210.

Yoon, Y. (2012). *Planning of optimal rehabilitation strategies for infrastructure using Time Float and Multiyear Prioritization Approach,* Ph.D. Dissertation, Purdue University, West Lafayette, IN.