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Balanced Allocation of Bridge Deck Maintenance Budget Through Multi-objective Optimization

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Abstract

Multi-objective optimization method for the allocation of bridge deck Maintenance, Repair, and Rehabilitation (MR&R) budget is proposed using Bridge Management System (BMS) models. In single-objective optimization method, the objective function is usually either total annual MR&R budget or structurally deficient deck area which must be minimized with given annual budget. These objective functions are minimized with constraints, and the solution methods are well-known for the most cases. In multi-objective optimization, objective functions can be the structurally deficient deck area as well as annual MR&R budget. Since structurally deficient deck area and level of annual deck MR&R budget are closely interrelated, State agencies need the method to balance the investment-deck improvement trade-off. This paper uses multi-objective optimization technique with linearly weighted sum method to find balanced MR&R alternatives for the network of bridge decks. Data obtained from Wyoming Department of Transportation (WYDOT) are used to validate the feasibility of application of multi-objective optimization for the maintenance of bridge decks.

Keywords: *Bridge Management System (BMS), Multi-objective optimization, bridge deck maintenance, probable unit cost, improvement model, and bi-objective optimization*

1. Introduction

Bridge Management Systems (BMS) are decision support tools that assist in the formation of optimal program for repair and rehabilitation for networks of bridges. It optimizes the allocation of MR&R budget for the network of bridges. Most common optimization modeling only optimizes single objective function. In bridge deck BMS, single objective function is usually total MR&R cost with aimed structural deficiency. Pontis (AASHTO, 2005), which is BMS software developed by American Association of State Highway and Transportation Officials (AASHTO), utilizes optimization technique to find the preservation policy which is the set of recommended preservation actions for the network of bridges. It also uses the objective function as the total expected discounted cost for the preservation actions. Miyamoto *et al.* (2000) developed BMS that identify bridge needs over planning horizon using genetic algorithm, and Hegagy *et al*. (2004), Morcous G. and Lounis Z. (2005), and Liu *et al*. (1997) proposed genetic algorithms for the optimization process along with Markov deterioration model to identify MR&R alternatives for the network of bridge decks. However, optimization used was single-objective optimization with objective function as the total cost for MR&R actions. Liu and Frangopol (2005) used multi-objective optimization with objective function being reliability based overall performance of bridge network and total maintenance cost over the specified time horizon. Lee and Kim (2007) used genetic algorithm to find optimal MR&R alternatives for network of bridges, but they used single objective optimization and considered one year of planning horizon.

Most optimization techniques used for finding optimal MR&R alternatives are single objective optimization, and deterministic unit costs for the maintenance actions are often used in optimization process. Due to the variety of MR&R actions and improvement offered by them, it is essential to model the cost using probability concept. Also using single-objective optimization for the allocation of MR&R budget produces more focused results related to its objective function.

This paper presents multi-objective optimization along with probable unit cost for the maintenance in allocating MR&R budget for the network of bridge deck. Optimization considers two interrelated objective functions at the same time: (1) percent of structurally deficient bridge deck area which is defined as percent area of bridge decks that have NBI deck condition rating [Recording, 1995] equal to or less than 4 and (2) total annual MR&R cost for network of bridge decks. The output of optimization

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is the set of balanced budget distribution parameters which allocate annual MR&R budget to the bridge decks in each NBI deck condition ratings.

2. Deterioration Model

Optimization for the allocation of bridge deck maintenance budget uses BMS models. BMS models consist of deterioration model, cost model, and improvement model. Deterioration model simulates the flow of deterioration for the network of bridge, and cost and improvement models predict the effect of MR&R actions on bridge decks. Recent BMSs like Pontis and BRIDGIT use stochastic Markov chains for the modeling of deterioration of bridge elements. In this research, Markovian deterioration model is used to predict the deterioration of bridge deck along with NBI bridge deck condition rating (Recording, 1995). In the US, the conditions of deck, superstructure, and substructure are reported on an integer scale from 0 (failed) to 9 (excellent). This is the National Bridge Inventory (NBI) condition rating and has been used since the 1970s. Table 1 shows the NBI bridge deck condition rating. Transportation agencies keep the records of the condition of bridge elements in the bridge inventory data file. WYDOT has the NBI deck condition rating data spanning from 1995 to 2014. These data are used as a basis for estimating the probable duration life in each bridge deck condition rating. Duration years in each deck condition rating are gathered to form probability distribution. According to Agrawal *et al*. (2010), distributions of duration years in each condition rating are typically skewed and as a result, not symmetrically distributed. Most commonly used distributions for durational phenomena are the Weibull and lognormal. DeLisle *et al.* (2003) found that the Weibull is the best distribution to represent durational phenomena for the bridge decks.

Using duration data and Weibull distribution, the probability distributions of duration years in each deck condition ratings are formed as shown in Fig. 1, and the median duration years in each deck condition ratings are computed. These median duration years are then converted to transition probabilities in Markov Transition Probability Matrix (MTPM) using Eq. (1) which can be found in AASHTO (2005).

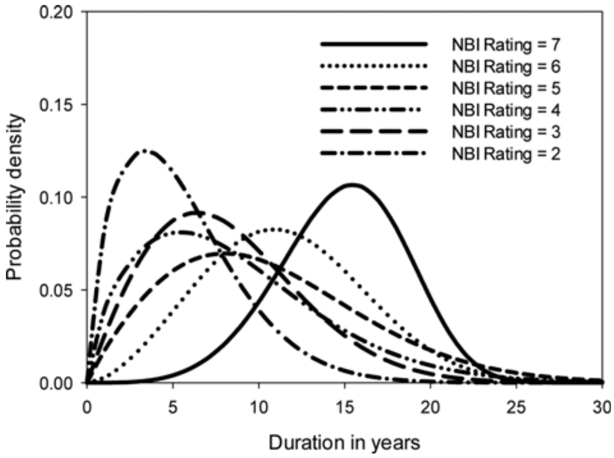

Fig. 1. Probability Distribution of Duration in Each NBI Deck Condition Ratings

$$p_{ii} = 0.5^{1/M} \quad (1)$$

where p_{ii} is the transition probability in MTPM which indicates the probability of remaining in the same condition rating during inspection cycle, and M is the median duration years in each condition state.

Equation (2) shows the formed MTPM for bridge decks. Diagonal elements in MTPM represent the probability of remaining in the same condition rating, and the elements next to the diagonal elements indicate the probability of deteriorating to the next lower condition rating. This value gives the probability that the deterioration process will result in condition rating j at time interval n given that it was in condition rating i at the previous step. For example, the probability of 0.045 in formed MPTM is the probability of deteriorating to the condition rating 6 at the time interval of 1 year given that it was condition rating 7 in previous step.

Using Markov deterioration models are practical as well as beneficial. They can capture the stochastic phenomena due to uncertainties in initial bridge deck condition, condition rating assessments, and deterioration. Also it is important to understand that in MTPM, the future transition of next lower condition rating depends only on current condition rating. With formed MTPM, the deterioration of bridge decks can be illustrated as

Table 1. NBI Condition Rating for Bridge Deck (Recording, 1995)

Rating	Condition State	Description
9	Excellent condition	No defects noted
8	Very good condition	No defects noted
7	Good condition	Some minor defects
6	Satisfactory condition	Structural components show minor defects.
5	Fair condition	All primary structural components are sound but may have some minor defects.
4	Poor condition	Advanced defects
3	Serious condition	Advanced defects seriously affect primary structural components.
2	Critical condition	Advanced defects of primary structural components.
1	Imminent failure condition	Major defects in critical bridge components. Obvious movement affect structural stability. Bridge is closed
0	Failed condition	Out of service, beyond corrective action.

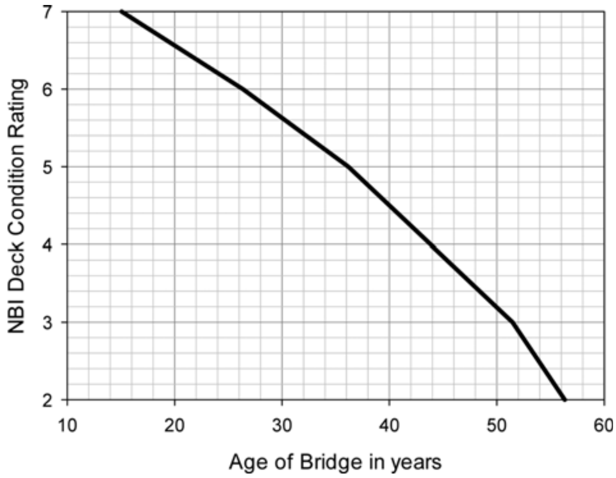

Fig. 2. Deterioration Model for Bridge Deck

shown in Fig. 2.

$$\begin{array}{c} \text{NBI Deck Condition Rating} \\ \begin{array}{ccccccc} 7 & 6 & 5 & 4 & 3 & 2 & 1 \end{array} \end{array}$$

$$\boldsymbol{T} = \begin{array}{c} 7 \\ 6 \\ 5 \\ 4 \\ 3 \\ 2 \\ 1 \end{array} \begin{pmatrix} 0.955 & 0.045 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.941 & 0.059 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.932 & 0.068 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.913 & 0.087 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.913 & 0.087 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.867 & 0.133 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \quad (2)$$

where $\boldsymbol{T}$ stands for the MTPM.

3. Probabilistic Models for Bridge Deck MR&R Cost

Deck MR&R actions are analyzed using WYDOT rehabilitation data spanning years from 2010 to 2014 (Cost, 2014 and Bid information, 2014). A total of 198 bridge rehabilitation data were studied for the type of deck MR&R actions, the NBI deck condition rating at the time of MR&R application, the deck rating after the application of MR&R action, the structural deficiency, and the unit costs associated with MR&R actions. The purpose of this analysis is to build probability models for various deck MR&R costs and to estimate the probable improvement and cost associated with it.

Study reveals that deck MR&R actions in WYDOT consist of deck repair (crack sealing and patching), deck rehabilitation (overlay after repair), and deck replacement. Deck MR&R cost is determined as unit cost per square foot of deck area. Since deck MR&R actions are always accompanied by other repair actions such as railing modification, resetting bridge rail, joint modification, approach slab replacement, etc., deck MR&R unit cost uses the concept of total unit cost. Total unit cost for deck MR&R actions include maintenance costs for other bridge elements in addition to directly related deck cost. Total unit cost for deck MR&R action will be very useful in estimating future bridge needs as it greatly simplifies the process and eliminates the need for developing deterioration models for other elements such as bridge rail, joint, curb, approach slab, etc. For example, deck deterioration model using NBI deck condition rating such as Markov model can be utilized to estimate whole MR&R costs for bridge deck.

In probabilistic modeling of deck MR&R cost, beta probability distribution is used since beta distribution is defined only in finite interval (which is more realistic as cost cannot be infinitely defined as does in normal distribution), and beta distribution has four adjustable parameters which give more flexibility to fit the observed sample data. Other distributions such as normal, weibull, and lognormal are also considered but it was found that beta distribution provides the best fit.

Figure 3 shows the formed probability distributions of total unit costs for deck MR&R. The variability of deck overlay (rehabilitation, REHAB) cost is higher than those for other deck MR&R actions since it was found that deck rehabilitation applied to the bridge deck with condition rating equal to as low as 3 to as high as 6. This wide application of deck rehabilitation makes huge variation on associated cost. Table 2 shows the computed deck MR&R cost with associated probability of cost.

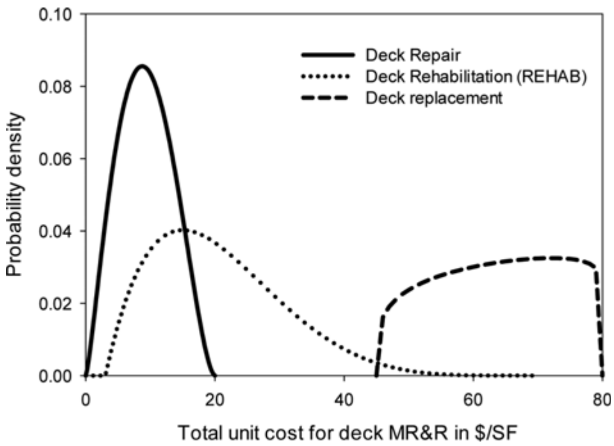

Fig. 3. Probability Distributions of Total Unit Cost for Deck MR&R Actions

Table 2. Total Unit Costs for Deck MR&R Actions and Associated Probabilities

Deck MR&R	Probability that deck MR&R action can be done within associated cost								
	10%	20%	30%	40%	Mean value, μ	60%	70%	80%	90%
Repair	$ 3.8	$ 5.4	$ 6.8	$ 8.0	$ 9.2	$ 10.3	$ 11.6	$ 13.0	$ 14.8
REHAB	$ 8.6	$ 11.5	$ 14.1	$ 16.5	$ 20.5	$ 21.9	$ 25.0	$ 28.9	$ 34.5
Replacement	$ 50.2	$ 54.1	$ 57.6	$ 61.0	$ 63.8	$ 67.4	$ 70.5	$ 73.6	$ 76.7

4. Improvement Model

The effect of deck MR&R action on the condition rating of bridge deck is analyzed by comparing NBI deck condition rating at the time of MR&R application with rating after the application of MR&R action. Historical rehabilitation data from WYDOT (Cost, 2014) are used for this purpose.

Figure 4 shows the improvement of deck by MR&R actions. If the rehabilitation is applied when deck condition rating equals to 3, then deck condition rating increases to 7 in 45% of observed population. Similarly, if the rehabilitation is applied when deck condition rating equals to 3, then deck condition rating increases to 6 in 45% of observed population. Using the historical observation of rehabilitation data, the deck improvement model by MR&R actions and associated unit costs are developed as shown in Table 3 and in Fig. 5. Eq. (3) shows the improvement MTPM using deck improvement model. For example, if the deck rehabilitation is applied when deck condition rating equals to 4, then 60% of bridge deck will be improved to condition rating of 7 and 40% of bridge deck will be improved to condition rating of 6. Associated MR&R action would be rehabilitation (REHAB), and cost would be the one that has the associated probability.

NBI Deck Condition Rating

$$\boldsymbol{T}_i = \begin{array}{c} 7\\6\\5\\4\\3\\2\\1 \end{array}\overset{\begin{array}{ccccccc}7 & 6 & 5 & 4 & 3 & 2 & 1\end{array}}{\begin{pmatrix} 1.0 & 0 & 0 & 0 & 0 & 0 & 0\\ 1.0 & 0 & 0 & 0 & 0 & 0 & 0\\ 0.67 & 0.33 & 0 & 0 & 0 & 0 & 0\\ 0.6 & 0.4 & 0 & 0 & 0 & 0 & 0\\ 0.5 & 0.5 & 0 & 0 & 0 & 0 & 0\\ 1.0 & 0 & 0 & 0 & 0 & 0 & 0\\ 1.0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}} \quad (3)$$

where $\boldsymbol{T_i}$ stands for the improvement MTPM.

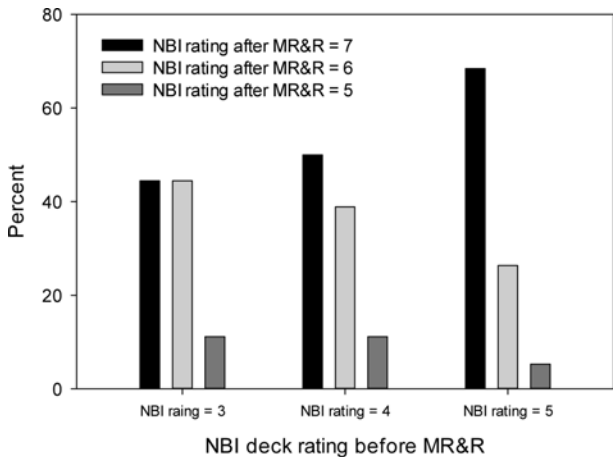

Fig. 4. Improvement of Deck Condition Rating by MR&R Actions

5. Problem Formulation for the Multi-objective Optimization

Most common optimization modeling only optimizes single objective function. Single objective optimization problem seeks to minimize or maximize single function as:

$$\min_{x \in C} f(x) \quad (4)$$

where *f(x)* is called objective function, and *C* is the set of equality and inequality constraints as shown below.

$$C = \{x : h(x) = 0,\ g(x) \le 0\} \quad (5)$$

The x is said to be feasible solution of function *f(x)* if $x \in C$, and the set of feasible solutions is called feasible region. For multi-objective optimization problem, there can be many objective functions. The multi-objective optimization problem can be written as:

Table 3. Deck Improvement Model and Associated Unit Cost

Deck condition rating before MR&R	3		4		5	
Deck condition rating after MR&R	7	6	7	6	7	6
Improved percent	50%	50%	60%	40%	66.67%	33.33%
MR&R action	REHAB	REHAB	REHAB	REHAB	REHAB	REHAB
Probability	90% of REHAB		Mean value of REHAB		30% of REHAB	

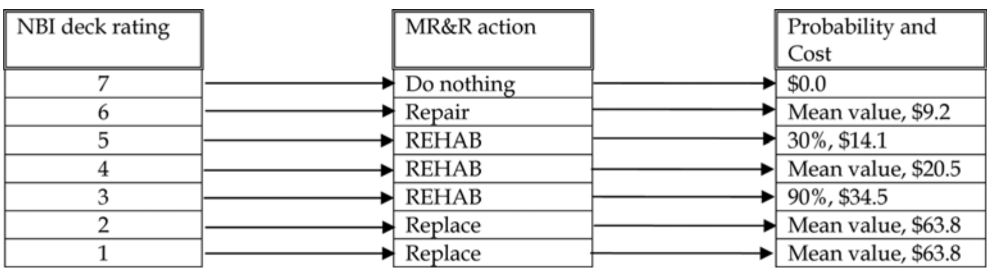

Fig. 5. Deck Improvement Strategies Along with Associated unit Costs

$$\min_{x \in C} F(x) = \begin{Bmatrix} f_1(x) \\ \vdots \\ \vdots \\ f_n(x) \end{Bmatrix} \quad (6)$$

where feasible solution and the feasible region can be defined similar manner as the single objective problem.

Usually, multi-objective optimization problem is difficult to handle because the objective functions are often contradictory. For example, structurally deficient deck area decreases as annual deck MR&R budget increases. Structurally deficient deck area and MR&R budget are the objective functions, and these are contradictory to each other. One possible strategy is to assign the weight to each objective function depending on their relative importance and then define single composite objective function as follows (Asghar, 2000).

$$F(x) = \sum_{i=1}^{n} w_i f_i(x) \qquad \sum w_i = 1 \quad (7)$$

where, w_i is the weight factor. In many applications of optimization problems, the objective functions are measured by various units. For example, structurally deficient deck area can be measured as percentage, and annual MR&R budget is measured as dollar amount. For that reason, the objective functions should be normalized. Stanimirovi *et al.* (2011) proposed normalization of objective function by manipulating the coefficients of objective functions. Let's denote $f_i^o(x)$ be the normalized i-th objective function, $f_i(x)$, which can be written as:

$$f_i(x) = \sum_{j=1}^{l} c_{ij} \times x_j \quad (8)$$

where, c_{ij} is the coefficient of j-th optimization variable of i-th objective function, and x_j are the variables in optimization, $j = \overline{1, l}$. Normalization of i-th objective function can be performed as:

$$f_i^o(x) = \frac{c_{i1}}{A_i}x_1 + \frac{c_{i2}}{A_i}x_2 + \ldots + \frac{c_{il}}{A_i}x_l \qquad A_i = \sum_{j=1}^{l} |c_{ij}| \quad (9)$$

Normalized composite objective function becomes:

$$F^o(x) = \sum_{i=1}^{n} w_i \times f_i^o(x) \quad (10)$$

It can be seen that now the coefficients have the values spanning from 0 to 1.

The two objective functions in multi-objective optimization problem are the percent of structurally deficient deck area and the total annual MR&R budget. These can be determined using BMS models formed in previous section. Prediction of future condition of deck would require summation of two parts, deterioration without MR&R actions and improvement with MR&R actions. Decks will be deteriorated if they do not receive MR&R actions in current time. The first term of Eq. (11) represents this part. Future conditions of decks will be improved if they receive the MR&R actions. This portion of deck can be represented by the second term of Eq. (11).

$$\boldsymbol{d}^t = \boldsymbol{d}^{t-1} \cdot \boldsymbol{X}_1^{t-1} \cdot \boldsymbol{T} + \boldsymbol{d}^{t-1} \cdot \boldsymbol{X}_2^{t-1} \cdot \boldsymbol{T}_i \quad (11)$$

where, dot, " · " indicates matrix multiplication. The variables in Eq. (11) can be defined as:

$\boldsymbol{d}^t$ = $\{d_7^t, d_6^t, d_5^t, d_4^t, d_3^t, d_2^t, d_1^t\}$, Condition vector of network of bridge deck area at t year. For example, d_5^t means percent of deck areas which have condition rating equal to 5 at year of t.

$\boldsymbol{d}^{t-1}$ = Condition vector of network of bridge deck area at t-1 year.

xV_i = The portion of d_i^{t-1} that receives MR&R actions at t-1 years.

$$\boldsymbol{X}_1^{t-1} = \begin{pmatrix} 1-xV_7 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1-xV_6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-xV_5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-xV_4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-xV_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-xV_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1-xV_1 \end{pmatrix},$$

Diagonal matrix of no maintenance, in which each diagonal elements indicate the portion of $\boldsymbol{d}$ that does not receive MR&R actions at t-1 year.

$$\boldsymbol{X}_2^{t-1} = \begin{pmatrix} xV_7 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & xV_6 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & xV_5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & xV_4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & xV_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & xV_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & xV_1 \end{pmatrix},$$

Diagonal matrix of maintenance, in which each diagonal elements indicate the portion of $\boldsymbol{d}$ that receives MR&R actions at t-1 year.

$\boldsymbol{T}$ = Deterioration Markov Transition Probability Matrix (MTPM).

$\boldsymbol{T}_i$ = Improvement MTPM.

The diagonal elements of maintenance matrix, xV_i, can range from 0 to 1 and this matrix relates the portion of deck that is improved by MR&R action. In Eq. (11), notice the recursive nature of improvement and deterioration algorithms. Future deck condition depends on current condition vector as well as maintenance matrix. The vector of future deck area in each NBI deck condition rating, $\boldsymbol{FA}$, can be determined as:

$$\boldsymbol{FA} = \boldsymbol{d}^t \times A_d \quad (12)$$

where, A_d is the total deck area in network of bridge.

Total annual MR&R budget is the first objective function in multi-objective optimization and can be computed as dot product between unit cost vector of $\boldsymbol{C}$ for the deck maintenance and improved deck area due to MR&R actions. The unit cost vector can be constructed using deck improvement strategy shown in Fig. 5 as:

$$\begin{array}{l} \text{NBI Deck Condition Rating} \\ \quad\ \ \underline{7 \qquad 6 \qquad 5 \qquad 4 \qquad 3 \qquad 2 \qquad 1} \\ \boldsymbol{C} = \{\$0 \quad \$9.2 \quad \$14.1 \quad \$20.5 \quad \$34.5 \quad \$63.8 \quad \$63.8\} \end{array} \tag{13}$$

Total annual MR&R budget is then computed as Eq. (14). The matrix product inside bracket of Eq. (14) represents the vector of improved deck area due to MR&R action.

$$f_1 = TB^t = [A_d \times \boldsymbol{d}^{t-1} \cdot \boldsymbol{X}_2^{t-1}] \cdot \boldsymbol{C} \tag{14}$$

where TB^t is the total annual MR&R budget.

The second objective function for optimization process is the percent of structurally deficient deck area which can be expressed using the elements of condition vector as:

$$f_2 = d_4^t + d_3^t + d_2^t + d_1^t \tag{15}$$

The two objective functions can be transformed into single composite objective function using weight factors.

$$\begin{aligned} F(x) &= w_1 f_1 + w_2 f_2 \\ w_1 + w_2 &= 1 \end{aligned} \tag{16}$$

Optimization process yields the set of elements of maintenance matrix, xV_i. They indicate the portion of deck area that receives the MR&R actions. Given the total annual cost for MR&R action, TB^t, maintenance matrix, $\boldsymbol{X}_2^{t-1}$, can be used to compute the vector of budget distribution parameters, $\boldsymbol{X}$.

$$\begin{array}{l} \text{NBI Deck Condition Rating} \\ \quad\ \ \underline{7 \quad 6 \quad 5 \quad 4 \quad 3 \quad 2 \quad 1} \\ \boldsymbol{X} = \{x_7 \quad x_6 \quad x_5 \quad x_4 \quad x_3 \quad x_2 \quad x_1\} \end{array} \tag{17}$$

where the elements of $\boldsymbol{X}$, x_i, means the portion of annual MR&R budget that should be spent on bridge deck with NBI deck condition rating equal to i. Thus, the vector of budget distribution parameters can be seen as the allocation of deck MR&R budget according to specific NBI deck condition rating.

The vector of budget distribution parameters is computed as:

$$X = \frac{\boldsymbol{C} \cdot diag[\boldsymbol{d}^{t-1} \cdot \boldsymbol{X}_2^{t-1}] \times A_d}{TB^t} \tag{18}$$

where, *diag*[ ] indicates diagonalization of vector to matrix.

6. Application

Multi-objective optimization for the allocation of bridge deck MR&R budget is performed for the group of bridge decks in WYDOT with 6 years of planning horizon. The initial percent area of structurally deficient deck is 12.1%, and the total bridge deck area considered is 2.91 million square foot. Optimization process is implemented using Mathematica program (Wolfram, 2015). The following constraints as shown in Eq. (19) are used in optimization process. The last constrains in Eq. (19) indicate the safety concern that bridge decks are always replaced or rehabilitated in priority when deck reaches its condition rating less than or equal to 3.

$$\begin{aligned} & xV_i \le 1, \qquad xV_i \ge 0 \\ & TB^t \le \$\,5,200,000 \\ & xV_3 = xV_2 = xV_1 = 1 \end{aligned} \tag{19}$$

Multi-objective optimization is solved by weight increment of 0.05 between 0 and 1. It was found that weight factors between 0.4 and 0.8 produce different optimized results for practical application. The weight of 0.4 produces more focused result to the second objective function (minimizing structural deficiency) while weight of 0.8 produces results focused to the first objective function (minimizing total budget). In this application, weight on the first objective function equal to 0.7 is used to produce the balanced result between two objective functions.

For the purpose of comparison, two single-objective optimizations are also performed. The first optimization has the objective function as the percent area of structurally deficient deck with annual budget as a constraint. This is called as optimization 1. The constraints for optimization 1 are the same as multi-objective optimization.

The second optimization has the objective function as the total annual MR&R budget with the constraint of targeted structural deficiency at each year. The structural deficiency of deck reduces 2% at each year and stay at 6% after it reaches. This is called as optimization 2. The constraints for optimization 2 are the same as multi-objective optimization except that targeted structural deficiency of deck is the constraint. Thus, optimization 1 minimizes the structural deficiency with given annual budget, whereas optimization 2 minimizes the total annual budget with targeted structural deficiency.

Figure 6 shows the percent of structurally deficient deck area vs. time in years. As a result of MR&R actions, structural deficiency decreases with time. Optimization 1 has the greatest reduction of structural deficiency, but total budget required is the highest. Optimization 2 has the least reduction on structural deficiency but saves the great amount of total annual MR&R budget. Two single optimizations show biased results close to their objective functions, respectively. On the contrary, multi-

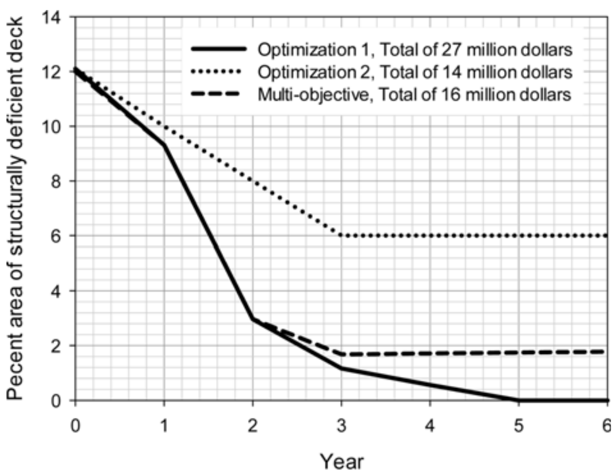

Fig. 6. Comparison of Optimization

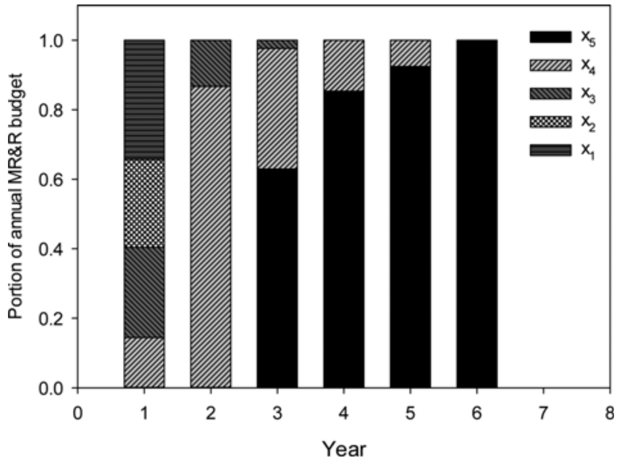

Fig. 7. MR&R Budget Allocation for "Optimization 1"

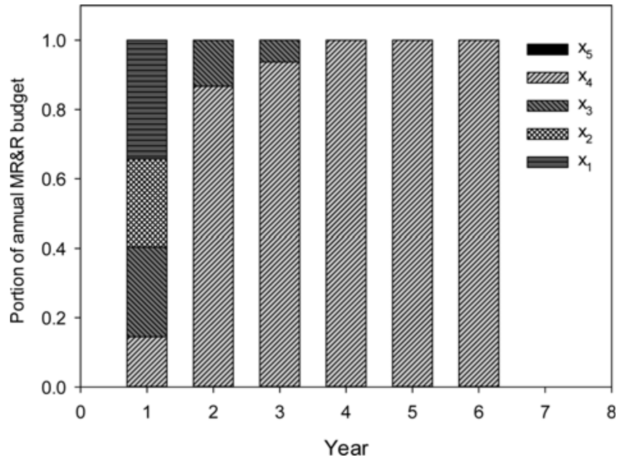

Fig. 9. MR&R Budget Allocation for Multi-objective Optimization

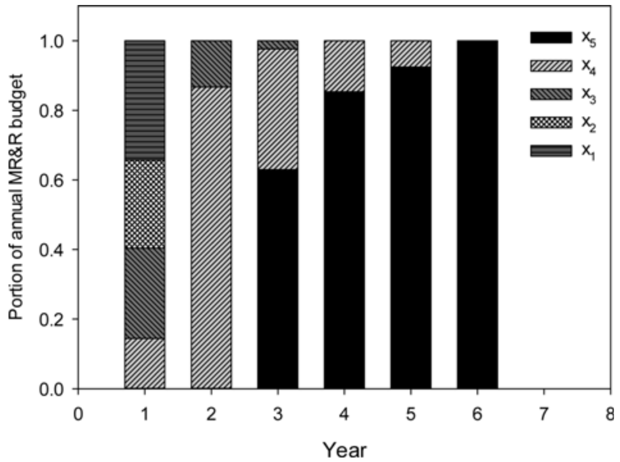

Fig. 8. MR&R Budget Allocation for "Optimization 2"

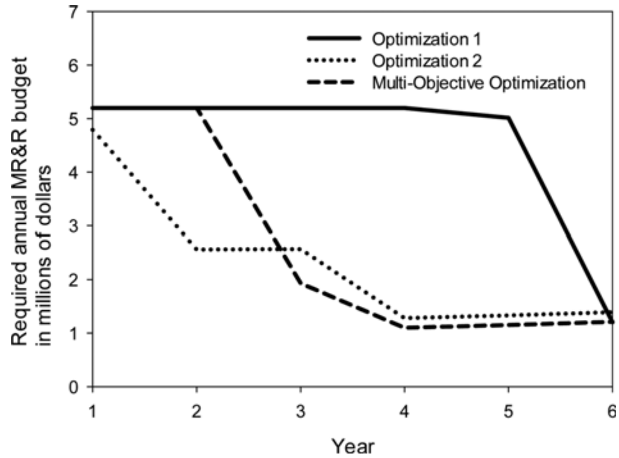

Fig. 10. Required Annual MR&R Budget

objective optimization shows balanced result in terms of total required annual budget and reduction of structural deficiency of deck. Total required MR&R budget is slightly higher than that for optimization 2, but multi-objective optimization reduces structural deficiency of deck close to 2%.

Figure 7, through Fig. 9 show the allocation of MR&R budget. Budget allocation for optimization 1 focuses on MR&R actions for structurally deficient deck for the first two years as shown in Fig. 7. After 2 years, MR&R budget is allocated to the bridge deck with NBI condition rating equal to 5. In fact, at 6^{th} year, 100% of MR&R budget will be spent on proactive maintenance actions. This would be the good strategy for the enough MR&R budget situation. Budget allocation for optimization 2 always focuses on MR&R actions for the structurally deficient deck only as shown in Fig. 8. There are no preventive MR&R actions in this optimization scheme, and there are always bridge deck areas with condition rating equal to 3. Fig. 9 shows the budget allocation for multi-objective optimization. Like optimization 2, MR&R budget is allocated to structurally deficient bridge deck only. But after 3 years, MR&R budget is only spending on bridge deck with condition rating 4. There are no bridge decks with condition rating equal to or less than 3. This is good for safety concern, and budget allocation pattern is in between optimization 1 and 2.

Figure 10 shows the required annual MR&R budget for 6 years of planning horizon. As expected, optimization 1 requires the greatest amount of budget for 6 years but, in return, there will be near 0% of structural deficiency of bridge deck. Optimization 2 requires least amount of budget but the improvement of bridge deck is least among 3 optimization schemes. Multi-objective optimization requires a little bit higher budget for the first 2 years but remains in least after 2 years and the return of investment is somewhat similar to optimization 1.

Application of three optimizations for the allocation of MR&R budget clearly shows that multi-objective optimization results in balanced results between total annual MR&R budget and reduction of structural deficiency of bridge deck.

7. Conclusions

Multi-objective optimization for the allocation of bridge deck MR&R budget is presented. Two conflicting objective functions used in optimization are: (1) percent area of structurally deficient deck and (2) annual MR&R budget for network of bridge deck. Markov deterioration model is used in optimization to predict future condition of network of bridge deck, and probable total unit cost for bridge deck maintenance is used rather than deterministic value of unit cost which allows the recognition of huge uncertainty associated with unit cost estimation. Total unit cost contains the cost for other bridge elements such as bridge rail, joint, curb, approach slab, etc. that are closely related with bridge deck maintenance. Use of probable total unit cost greatly simplifies on estimation of bridge deck needs for the future by eliminating the need of developing deterioration models for other elements.

For the purpose of forming probability distribution of total unit cost and the effect of bridge deck maintenance, historical rehabilitation data from WYDOT are analyzed. Data are studied for the type of deck MR&R actions, improved NBI deck condition rating, structural deficiency, and unit costs associated with MR&R actions. Based on analysis, improvement model in terms of improvement Markov Transition Probability Matrix is constructed. BMS models including deterioration model, probable model for bridge deck MR&R cost, and improvement model are then used in optimization process.

For comparison purpose, two single-objective optimizations are performed along with multi-objective optimization. It is found that single-objective optimization shows biased result close to objective function. For example, if objective function is minimizing percent of structural deficiency of deck, the result of optimization reduces the percent of structural deficiency in expense of required MR&R budget and vice versa for the opposite case. On the contrary, multi-objective optimization produces the balanced results. It greatly reduces the percent of structural deficiency of deck with much less amount of required MR&R budget. The benefit of using multi-objective optimization is balancing the objective functions according to State agenc's policy. Future research is needed for developing the realistic deterioration model after the MR&R actions taking place. In this research, it is assumed that bridge deck deterioration after MR&R action is the same pattern as that for new bridge deck, but this assumption may not be realistic. New deterioration model is needed to be integrated with BMS models to accurately predict the future condition of bridge deck.

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