Bridge Deck Management System with Integrated Life Cycle Cost Optimization

ABSTRACT

Bridge Management Systems have been classified as one of two options: network-level and project-level. While the former type concerns with the prioritization of bridges for inclusion into an upcoming MR&R program, the latter is focused on the types of repair that suit the components of a selected bridge. While both decisions are inter-related, most bridge management research has dealt with them as separate aspects, thus may lead to neither being globally optimum. This paper presents a comprehensive framework for bridge-deck management system that aims at integrating project-level and network-level decisions into a unified model so that costs are optimized at both levels. The novelty of the proposed approach stems from three main aspects: (1) incorporating project-level repair options along with their performance improvements and cost implications; (2) incorporating many flexible and practical features such as variable yearly budget limits, variable yearly discount rates, and optional methods for handling project-level repairs (e.g., single or multiple visits); and (3) using a powerful Genetic Algorithm-based optimization to consider both project-level and network-level variables into bridge Life Cycle Cost optimization. A description of the proposed model and its implementation are presented along with an example application. While this research focuses on bridge decks, details on future improvements to incorporate all bridge components are outlined.

INTRODUCTION

Bridges are vital links in roadway networks as their failure may cause excessive public/private losses. It is essential, therefore, to establish an effective maintenance/repair strategy in order to keep bridges sufficiently safe and serviceable throughout their service lives. However, with most existing bridges being old and the funds available for repair being limited (1), decisions related to the prioritization of bridges for repair purposes, the allocation of the limited funds, and the selection of appropriate repair methods become complex. To support municipalities and large owner organizations in that regard, Bridge Management Systems (BMS) have emerged (2).

While the selection and prioritization of bridges can be considered a network-level decision, selection of repair methods for individual bridges and their components can be considered as a project-level decision. In the literature, various BMS systems have been developed to support either project-level or network-level decisions, and to a lesser extent, to support both of them. Figure 1 presents a brief summary of the research efforts in developing BMS systems, with brief outline of their pros and cons.

While decisions at both network-level and project-level are inter-related, most bridge management research has dealt with them as separate aspects, thus may lead to neither being optimally decided. At the network-level, Li et al. (3) developed a www-based prototype BMS. The model produces a sorted list of bridges which gives higher priority ratings to bridges with greater needs for maintenance and rehabilitation. At the project-level, on the other hand, focus is mainly on selecting the repair method (e.g., 0: do nothing, 1: maintenance, 2: rehabilitation, and 3: replace) for a selected bridge (4). In this case, details on the specific repair method, cost, and expected improvement are considered. The Finnish project-level BMS (5), for example, uses the recommendations from the network-level BMS to decide on a repair strategy for individual bridges based on Life-Cycle Cost Analysis (LCCA) principles. Other models, e.g., Reel and Conte (6) use the present value and incremental cost-benefit ratio analysis to decide on the repair types.

Some of the limited but increasing efforts related to incorporating both network-level and project-level decisions can be found in (7, 8, 9, and 10). Thompson et al. (7) is an example of a good effort to combine both levels using a cost-benefit analysis. However, incorporating project-level details into network-level analysis complicates the LCCA and makes traditional optimization tools insufficient to deal with the large formulation involved. This is particularly the case when hundreds of bridges are involved (8). To handle such large optimization problem, the Genetic Algorithms (GAs) technique was introduced by many researchers as a non-traditional optimization tool for BMS. Miyamoto et al. (9), for example, developed the Japan-BMS to detect the deterioration of bridge components and determine the appropriate repair method. In this system, the GAs technique was used to search for the optimum maintenance plan. Another example, (10) developed a network-level BMS to optimize the selection of maintenance strategy using GAs. Despite of the increasing trends in developing integrated BMS systems, existing research (as
shown in Fig. 1) still has some drawbacks related to modeling complexity, which the present research is attempting to overcome.

### FIGURE 1 Types of bridge management systems.

Many BMS systems have dealt specifically with bridge decks, which is the most deteriorated component of bridges. The project-level BMS of Markow (11) suggested a life-cycle cost approach to decide on the time and methods of improving bridge decks. At the network-level, Jacobs (8) used an integer programming approach to optimize long-term bridge deck rehabilitation and replacement plans. At the combined level, Dogaki et al. (12) presented an optimization model for maintenance planning of reinforced concrete bridge decks using GAs. This model considers selecting the repair method and allows multiple bridge visits during planning horizon.

While existing BMS systems have incorporated many useful features, they still have some drawbacks that may hinder the actual execution of their resulting plans. These include: may use approximations to simplify and avoid large complex analysis; may not consider multiple repairs along an asset life; and do not consider perceived execution constraints such as deadlines and resource limits.

This paper presents a comprehensive and transparent model to assist decision makers for the optimum selection of maintenance and repair strategies of bridge decks, integrating both project-level and network-level decisions. The model developments and its implementations on a spreadsheet are outlined and a numerical example is presented to demonstrate the applicability of the proposed model. The output of the model is a set of planning strategies for the maintenance and repair throughout the planning horizon. Future work to incorporate all bridge components is then outlined.

### COMPONENTS OF A UNIFIED BRIDGE MANAGEMENT SYSTEM

The main components of a generalized BMS that incorporates both project-level and network-level decisions are as follows (Figure 2):
- Detailed BMS models (time-dependent deterioration, repair cost, and repair-dependent improvement).
- BMS constraints (industry, governmental, political, user defined constraints, project, network, and execution constraints such as deadline, resources, etc.)
- BMS decision support module (user interface, condition assessment, LCCA, optimization).
FIGURE 2 Components of a unified bridge management system.

**BMS Models**

*Deterioration Model*

A BMS requires a deterioration model that estimates the future decline in bridge condition so that an appropriate rehabilitation strategy can be decided (13). In this research, one of the most common models, Markovian deterioration model, is used to predict future bridge condition (14). The Markov deterioration model assumes that bridge condition state takes a value from 0 to 9 (according to FHWA ratings). The model starts from a known (or estimated) probability transition matrix, for example, Equation 1 represents a probability transition matrix for steel interstate highway bridge deck slabs (15). Each row of the matrix has two values that represent the probability of the deck to remain in its condition state and the probability of moving to the next lower condition state. An important assumption for the probability transition matrix is that the transition to the next lower state is dependent only on current state and not on any other attribute, including time.

\[
P = \begin{bmatrix}
0.633 & 0.367 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

(1)
For bridge decks, the present study uses the probability transition matrices proposed by Jiang (15) for different bridge materials, highway types, and age ranges. Using these matrices, the deterioration of steel bridge decks, for example, can be represented as shown in Figure 3.

FIGURE 3 Deterioration model for steel bridge deck.

Cost Model

In this paper, three repair options are used for bridge decks and the cost of repair is estimated as a percentage of initial (or total replacement) cost: light repair, medium repair, and extensive (full replacement) repair. Light repairs are intended to restore the deck surface and include patching, sealing, and cleaning of debris. Medium repairs, on the other hand, involve strengthening or increasing bridge deck thickness, and, as such, may require closure of the bridge to traffic. The third repair option is the extensive repair or deck replacement and requires a complete closure of the bridge to traffic. The costs associated with these repair options are estimated to be, 28.5%, 65%, and 100%, respectively (16).

Improvement Model

The impact of each repair option on the condition of a bridge deck is important to be analyzed. As represented by Seo (16), estimated repair improvement is shown in Table 1. The improvement values are represented graphically in Figure 4. This figure shows that, to raise the bridge deck from condition 3 to condition 5, a medium repair should be selected while to raise it to condition 7, extensive repair should be selected.

TABLE 1 Impact of Repair Option on Bridge Deck Condition

<table>
<thead>
<tr>
<th>Condition Rating before Rehabilitation</th>
<th>Condition Rating after Rehabilitation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5, 6</td>
</tr>
<tr>
<td></td>
<td>7, 8</td>
</tr>
<tr>
<td>3, 4</td>
<td>Medium</td>
</tr>
<tr>
<td>5, 6</td>
<td>Light</td>
</tr>
<tr>
<td>7, 8</td>
<td>Light</td>
</tr>
</tbody>
</table>

BMS Constraints

As shown in Figure 2, several constraints should be taken into account in a BMS including: available technology, governmental, political, user, project, and network constraints. A general BMS should be able to consider all practical constraints imposed on a bridge not only at the project and network levels but also at the user, government, and municipality levels as well. In addition, an important aspect that is overlooked in existing BMS systems is to consider several execution constraints such as the order of execution of individual bridges, deadline, resource limits, scheduling of in-house workforce versus employed contractors, and time/cost control. These are important aspects that, while being beyond the scope of this paper, are important to consider in the design of a general BMS.
BMS Decision Support

Bridge Condition Assessment

Several rating systems have been developed to assess the condition assessment of bridges. As shown in TABLE 2, the bridge condition rating used in this paper was developed by the FHWA (17), which uses a scale from 0 to 9 for bridge elements. It is assumed that bridges are serviceable until the rating reduces to a value of 3 (non-serviceable). Condition ratings are used to describe the existing condition of a bridge. It is considered as the most important phase on which subsequent decisions are based. Bridge condition is determined based on detailed assessment of the deck and all other bridge components, which is a large research area that is outside the scope of this paper.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Not applicable</td>
</tr>
<tr>
<td>9</td>
<td>Excellent condition, new condition: No noteworthy deficiencies</td>
</tr>
<tr>
<td>8</td>
<td>Very Good condition: No repair needed</td>
</tr>
<tr>
<td>7</td>
<td>Good condition: some minor problems for minor maintenance</td>
</tr>
<tr>
<td>6</td>
<td>Satisfactory condition: some minor deterioration for major maintenance</td>
</tr>
<tr>
<td>5</td>
<td>Fair condition: minor section loss, cracking, spalling, or scour for minor rehabilitation, minor rehabilitation is needed</td>
</tr>
<tr>
<td>4</td>
<td>Poor condition: Advanced section loss, deterioration, spalling or scour for major rehabilitation</td>
</tr>
<tr>
<td>3</td>
<td>Serious condition: section loss, deterioration, spalling or scour have seriously affected primary structural components for immediate rehabilitation</td>
</tr>
<tr>
<td>2</td>
<td>Critical Condition: Advanced deterioration of primary structural elements for urgent rehabilitation. The bridge may be closed until corrective action is taken</td>
</tr>
<tr>
<td>1</td>
<td>Imminent failure condition: Major deterioration or section loss present. Bridge may be closed to traffic but corrective action may put back in light service</td>
</tr>
<tr>
<td>0</td>
<td>Failed condition: out of service and is beyond corrective action</td>
</tr>
</tbody>
</table>

Life-Cycle Optimization Using GAs

Having defined the present condition of a network of bridges with the deterioration model, repair alternatives, and improvement model, the proposed BMS uses a GA-based optimization model to determine optimum priority list of bridges and their repair methods. The procedure searches for the optimal repair types and the times to perform these repairs, satisfying the budget and condition rating constraints.
Genetic algorithms are computerized search methods based on the theories of genetics and natural selection developed by Holland (18). Typically, GAs require a representation scheme to encode feasible solutions to the optimization problem. Usually this is done in the form of a string called a chromosome. Each chromosome represents one member (i.e., one solution) that is better or worse than other members in a population. The fitness of each chromosome is determined by evaluating its performance with respect to an objective function. To simulate the natural “survival of the fittest” process, one approach is to let best chromosome exchange information to produce offspring chromosomes that are evaluated in turn and can be retained only if they are more fit than others in the population (19). Usually, the process is continued for a large number of offspring generations in which the population gets enhanced and an optimum chromosome is arrived at. Due to their perceived benefits, GAs have been successfully adopted to solve many science and engineering problems (20).

Implementing the GAs technique for the problem at hand involved four primary steps: 1) setting the solution representation (called chromosome in GA terminology); 2) deciding the evaluation criterion (objective function); 3) generating an initial population of solutions; and 4) applying crossover/mutation to generate offspring chromosomes. Chromosome structure is made of a string of values associated with problem variables. As shown in Figure 5, a solution (chromosome) is made up of a string of \( N \times T \) elements, where \( N \) is the number of bridges and \( T \) is the planning horizon (5 years). Each of the chromosome elements has a value from 0 to 3 corresponds to one of the repair options (0 = do nothing, 1 = light repair, 2 = medium repair, and 3 = extensive repair).

![FIGURE 5 Chromosome structure.](image)

To evaluate a possible solution (chromosome), the objective function was constructed by summing the present value of the annual cost of repair for all bridges (Equation 2). The objective function, as such, is used to minimize the total life-cycle cost (TLCC), while maintaining acceptable bridge conditions (minimum rating value).

\[
\text{Min } TLCC = \sum_{t=1}^{T} \sum_{i=1}^{N} \frac{C_{it}}{(1 + r)^t}
\]

Where, \( C_{it} = \) Cost of bridge \( i \) at time \( t \); \( r = \) discount rate; \( T = \) number of years; and \( N = \) number of bridges. It is noted that the summation of the present worth values in the objective function is performed annually to allow the evaluation of annual costs versus cash flow limits. Added to the objective function, the proposed BDMS accounts for the following constraints:
1. Yearly LCC should be \( \leq \) yearly budget limits;
2. Condition rating of individual bridges \( \geq 3 \) (minimum acceptable level to FHWA);
3. Network overall condition rating is \( \geq \) Pre-defined user desirable value; and
4. Repair method used in a specific year for a specific bridge = user-forced value.

With the objective function and constraints defined, the GA evolutionary procedure takes place on a population of parent chromosomes. The simplest way to generate that population is randomly. In the present application, the user is given the flexibility to input the population size. Once the population is generated and the fitness of each
chromosome in this population evaluated using the objective function. The reproduction process among the population members takes place by either crossover or mutation. Crossover (marriage) is by far a more common process \( (21) \) and can be conducted by selecting two parent chromosomes, exchanging their information, and producing an offspring. Each of the two parent chromosomes is randomly selected in a manner such that its probability of being selected is proportional to its relative merit. This ensures that best chromosomes have higher likelihood of being selected. Also, the exchange of information between the two parent chromosomes is done through a random process to produce a one offspring. As opposed to crossover, mutation is a rare process that resembles the process of a sudden generation of an odd offspring that turns to be a genius. This can be done by randomly selecting one chromosome from the population and then arbitrarily changing some its information. The benefit of the mutation process is that it can break any stagnation in the evolutionary process, avoiding local minima. Many cycles (thousands) of offspring generations are conducted and population is evolved with more-fit offspring chromosomes until an optimum solution is reached or a stop criterion is met \( (21) \).

**PROTOTYPE AND EXAMPLE**

The proposed bridge deck maintenance/repair model and the GA procedure were implemented on a commercial spreadsheet program. In this study, Microsoft Excel software is selected for the implementation of the proposed model because of its ease of use and powerful programming features.

**FIGURE 6 Main worksheet showing user inputs.**

Using the Macro Language of Microsoft Excel, various procedures were coded to form a complete Bridge Deck Management Systems (BDMS). These developments involved a substantial effort in coding the various components and providing a user interface. The BDMS system includes different worksheets and user forms. The data of a network of bridges are input to the BDMS as shown in Figure 6 (a small 10-bridge network is used for demonstration purposes). For each bridge, data inputs are: construction year; initial cost; deck type (steel or concrete); highway type (interstate or others); average daily traffic (ADT); width; length; and condition in last inspection (present condition). Other inputs that represent the model variables are the deck repair method associated with every year within the planning horizon. These will be given optimum values using the GA optimization. The user, however, can override any determined values by entering his/her desired value. This, as such, provides the flexibility to cater for political constraints on using specific repair method in a given year. It is noted that the model variables work at both network-level and project-level decisions. If, for example, the deck repair types selected for a certain bridge are all zeroes in all the planning horizon years, this acts as a network-level exclusion of this bridge from the repair list (i.e., bridge has low priority). Inversely, when a bridge can have more than one repair type in different years along the planning horizon, and as such, the optimum repair strategy becomes a multiple repair visits forced by user: medium repair at year 3.
to such bridge as a high priority one. Also, as one of the flexible options of the model, the number of repair visits to a certain bridge can be constrained to a user-desirable maximum number, for practicality reasons (reduce traffic interruption, etc.). In the present example, this option is not utilized (i.e., multiple repair visits are allowed, with no limit specified on the maximum number of visits).

Once the bridge data are input, the user can start the optimization and the “Optimization Strategy” form appears as shown in Figure 7. In this form, the user can define the network-related constraints (e.g., minimum rating for the overall network = 6 and minimum rating for individual bridges = 5), and organizational-related constraints such as yearly budget limit, yearly discount rate, and the cost percentages associated with the three repair options. These inputs are fixed during the optimization; however, the user can change these values and re-optimize to examine the sensitivity of the results to budget limits, for example. The user, also, can define the desirable average condition for the bridge network and for each individual bridge as shown in Figure 7.

![Optimization Strategy Form](image)

**FIGURE 7 Optimization criteria screen.**

With the 10 bridges of the small network shown in Figure 6, a 5-year planning horizon, and 4 repair options, the number of possible solutions is 450, which is a huge number. The benefit of the GA procedure, therefore, is to arrive at near optimum solution by searching only a fraction of this large solution space. Once the user activates the optimization process, the evolutionary process starts and continues for the desired number of offspring chromosomes (input by user). The results of the current example are shown in Figure 8. The left side of the figure shows the optimized repair decisions associated with minimum life cycle cost ($27,076,000). As shown, some of the bridges are selected for repairs while others are not (e.g., bridges 2 and 10, which show high condition rating in column “C” of the model). The results also show logical repair decisions for bridges 1 and 9, which started with a low condition rating of 4.5, for both. Accordingly, the cheapest solution produced by the BDMS was to perform minor repairs for bridge 1 at years 1, 2, and 4. For bridge 9, on the other hand, a medium repair in the first year, in addition to a minor repair at year 3 were decided.

As shown in Figure 8, the overall network rating was 6.613, which is higher than the constraint used in this example. Similarly, all individual bridges show a rating in each year that is higher than the constraint used. The results of this simple example clearly show the good performance of the proposed BDMS and its ability to optimize complex decisions at both the network and project levels. It is noted that the solution determined in Figure 8 is close to global optimum. Further manually changes to the values of the model variables did not improve the resulting solution.
DISCUSSION AND FUTURE WORK

The model presented in this paper has been demonstrated to work effectively on the example application. Further experimentation was conducted on different combinations of bridges with different properties, and the model proved to consistently produce near-optimum results. In addition to its expandable structure, some of the flexible features of the proposed BDMS that make it an efficient management system for bridge decks include:

- User can specify desired repair type and time of that repair;
- Optimization process can respect desirable condition rating for individual bridges;
- Can maintain a desirable overall network rating;
- Consider variable budget limit/year;
- Consider variable discount rate/year; and
- Consider single or multiple visits (repairs) along the planning horizon.

Being a preliminary research in bridge management systems, the present model has a number of areas in which it can be improved (currently being pursued by the authors), including:

- Incorporate salvage value at the end of the planning horizon;
- Incorporate user cost in the LCCA (detours, reduction in user speed, and delay cost);
- Consider the cost of traffic controls at bridge sites in the optimization process, which is a function of repair type and the number of lanes involved;
- Include the subcomponents of the deck; such as: expansion joints, overlay, sidewalks, and curbs. In practice, it might be optimal to repair all the deck components at the same time, instead of repairing each one separately, even if these components are not in urgent need of repair. The target is to find the optimal time of repair, in which most of the components are approaching its end life;
- Extend the model to include other bridge components. The repair decisions of the deck should be related to the condition of other bridge components to minimize frequent traffic disruption;
- Develop a reliable deterioration model for the deck after repairs; and
- Incorporate a module to assist in the execution planning of the selected bridges to meet deadlines and ensure that the perceived benefits of the bridge management system are materialized.

CONCLUSION

In this paper, literature related to network-level and project-level bridge management systems has been reviewed and a model is presented to integrate both levels into a unified bridge management system. The proposed model incorporates a genetic algorithm procedure to optimally prioritize bridges for repair purposes and also select the suitable repair option for bridge decks. The developed model is flexible and allows a bridge deck to be selected for
repair more than once during the planning horizon, according to its repair needs. The model was implemented on a spreadsheet program to utilize its familiar interface and powerful functions. Macro programs were written to facilitate user input of bridges' data, and activate the genetic algorithm procedure. An example application was then presented to demonstrate the practicality and powerful capabilities of the BDMS prototype.

REFERENCES