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Implementation of Bridge Management Systems in State Highway Departments in the United States of America

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Abstract
The National Bridge Inventory of the United States includes a 25% of deficient bridges, either structurally deficient or functionally obsolete. Deficient bridges require major maintenance, repair, or replacement (MR&R) activities to satisfy the safety and serviceability requirements. The MR&R activities require a total budget of 15 billion USD, while the available funds by the Federal Highway Administration does not exceed 2 billion USD per year. Due to the budget deficit, bridge management systems (BMSs) are required to select the most cost-effective maintenance strategies.

This paper presents the use of bridge management systems, mainly Pontis, in the United States in different state departments of transportation (DOTs). Technical features of BMSs are reviewed, as well as user comments on the effectiveness of BMSs in daily applications. The results of this study show that major features of BMSs are not used in several DOTs. Hence, partial advantages are only exploited.

Keywords
Bridge Management Systems, Pontis, Deficient Bridges, Bridge Conditions, Budget Deficit

1. Introduction

The National Bridge Inventory (NBI) of the United States includes more than 600,000 bridges, including bridges located on interstate highways, US highways, state and county roads, and public-accessible bridges on federal lands. The NBI analyzes the bridges according to their geographical location, material of construction, span, and general condition. The Federal Highway Administration (FHWA) established National Bridges Inspection Standards (NBIS) for the evaluation of bridge conditions. States are required to inspect their bridges and report their condition to the FHWA using procedures and formats outlined in the Recording and Coding Guide for the Structures Inventory and Appraisal of the nation's bridges.

According to the NBI survey in the period from year 1992 to year 2000, 1 in every 4 bridges in the United States is deficient, either structurally deficient or functionally obsolete. Structural deficient bridges include all bridges with severe deterioration in one or more of the bridge components (i.e. bridge substructure, bridge superstructure, or bridge deck). The deterioration is enough to reduce the original load carrying capacity of the bridge. The majority of structural deficiency result from increasingly applied live loads, environmental attacks (i.e. scour, freeze and thaw cycles), and the use of de-icing chemicals. Functionally obsolete bridges are those with inadequate geometry, such as insufficient lane width, small radius of curvature, approach alignments problems, and insufficient under-clearance. Bridges mal-functioning is a direct result of increasing vehicle sizes and higher traffic volumes.

The maintenance, repair, and replacement (MR&R) activities required to satisfy the new serviceability and safety requirements determined by the FHWA require an annual budget of 15 billion USD. However, the current resources allocated for the MR&R of bridges does not exceed 2 billion USD per year. The severe budget deficit might subject several bridges within the inventory to the risk of severe deterioration or catastrophic collapse, as seen recently in the Missouri river bridge in year 2008. The backlog of MR&R activities necessitates the use of decision support tools to optimize the allocation of the scarce resources. Therefore bridge management systems (BMSs) are increasingly used by the FHWA, State Departments of Transportation (DOTs), and transportation agencies as decision support tools for selecting optimized short and long term plans to preserve the conditions of the nation bridge network under budget constraints

2. Literature Review

A BMS can be defined as a rational and systematic approach for making consistent and cost-effective decisions regarding the optimal allocation of the limited annual budget on the maintenance, rehabilitation, and replacement needs of bridge networks (Hudson et al., 1987). The main functions of BMSs are:

- Support transportation engineers to produce optimized short and long-term strategies for bridge MR&R activities.
- Ensure cost-effectiveness of operations and maintenance activities.
- Archiving the current bridge conditions for future decisions.

Typical BMS consists of four basic modules: database module, performance prediction module, cost module, and optimization module (Czepiel, 1995). The afore-mentioned modules are organized in Figure 1according to their dependencies (i.e. the arrow points to dependent module)

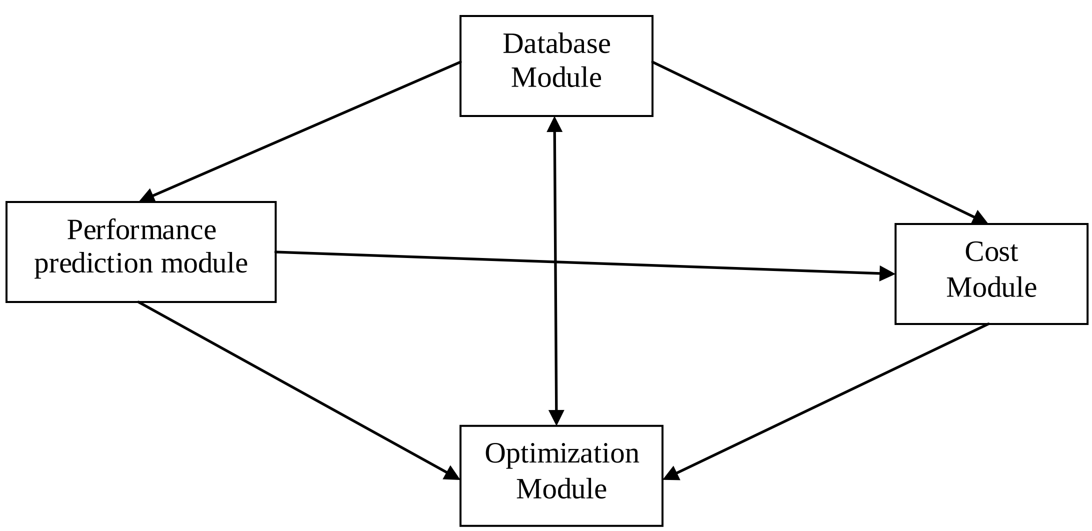

Figure 1: Typical BMS modules

The database module, sometimes called inventory module, is the foundation of any BMS. It stores all the bridge inventory, structural specifications data, administration data, inspection, appraisal, and maintenance data. The data stored in the data base module is used by other BMS modules as a basis for the analysis and decision making process. The performance prediction module function is dependent on the database module. The performance prediction module is responsible for predicting the conditions of each component within the bridge along the bridge life cycle. The component predicted condition is dependent on the MR&R actions taken and added to the database module.

To date, several BMS are adopted in different countries. The Federal Highway Administration (FHWA) supported the development of a BMS under the name Pontis. The Inter-Modal Surface Transportation Efficiency Act (ISTEA) of 1991 has recognized the needs of transportation agencies for decision support tools and mandated the use of BMS for maintenance planning in every bridge network. Pontis is currently the most popular BMS in the United States, adopted in forty two states. Internationally, Pontis is adopted by the ministries of transportation in Hungary, Kuwait, Portugal, Italy, and the island of Hokkaido, Japan.

In Canada, the Ministry of Transportation of Ontario (MTO) developed the Ontario Bridge Management Systems (OBMS) for managing their bridge network that includes approximately 3000 bridges on the provincial level (Thomson et al., 2003). OBMS is a completely different product from Pontis and is considered the most advanced BMS in Canada. A review of the technical features of both Pontis and OBMS is presented in the next section, followed by users' comments on adopting BMSs in different State DOTs.

3. Technical Review

3.1. Database Module

A key issue in the success of any software system is how the data required by this system are represented. BMSs are softwares that depend on different type of data to perform their intended functions. These data can be categorized into inventory, inspection, appraisal, and maintenance data. Inventory data, sometimes called static data, are those related to infrequently changing bridge features. Inventory data consist mainly of administrative, technical, and descriptive data. Inspection data are those used to describe the conditions of bridge components as a result of their visual inspections, condition surveys, and special inspections. Appraisal data are those used to evaluate the overall bridge performance based on condition indices derived from the inventory and inspection data or from detailed load rating analysis. Maintenance data are those used to describe the actions taken to maintain or improve bridge safety (e.g. deck replacement and column strengthening) and/or bridge serviceability (e.g. deck widening and curb repair). Bridge inspection, appraisal, and maintenance data are called dynamic data or time-dependant data because they are frequently changing during the bridge service life.

3.2 Performance Prediction Module

Bridge deterioration modules represent a main constituent of any BMS. They are responsible for the prediction of future bridge element conditions, and therefore specifying future maintenance needs. Several parameters determine the accuracy of deterioration module, such as the mathematical model used, size of the bridge network, and type of inspection. The mathematical models used to describe bridge deterioration are either deterministic, such as deterioration curves, or stochastic, such as Markov-chain models. The later one is adopted by the current BMSs used in the United States and Canada.

Markov chains are the most commonly used stochastic techniques for modeling and predicting the performance of different types of infrastructure facilities such as pavements, bridges, sewer pipes and water mains. Markov-chain models are based on the concept of probabilistic cumulative damage, which predicts changes of bridge element condition over multiple transition periods (Bogdanoff, 1978). Markov-chains are used for performance prediction by defining discrete condition states and accumulating the probability of transition from one condition state to another over multiple discrete time intervals. These transition probabilities are represented by a matrix called the transition probability matrix, where each cell represents the probability that the condition of a bridge component will change from one state to another state during a certain time interval called the transition period. Figure 2 shows an example of bridge element whose condition is described by four discrete condition states. Transition probabilities are also shown on the top of each arrow for a five year transition period. According to Figure 2, a new bridge element (at condition 4) has a probability of 80% to remain in condition 4 after 5, and a probability of 20% to move to condition 3 after the same period. These probabilities can be multiplied to determine the condition distribution after several transition periods.

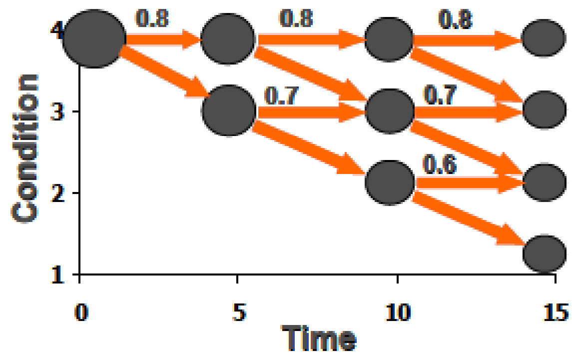

Figure 2: Markov-chain deterioration model

Transition probabilities are obtained for different bridge elements through either expert judgment or by the analysis of historical condition data accumulated in the database module. In Pontis, for each bridge element, there are four possible environmental categories that the element can be subjected to. The four categories are shown in Table 1. Each category represents a different level of impact of external factors (e.g. traffic, freeze-thaw cycles, and use of de-icing chemicals) on the element performance over time. The objectives of these categories are to account indirectly for the influence of these factors on the element deterioration rate and to differentiate between the deterioration of similar elements subjected to dissimilar environments. Four different transition probability matrices are developed for each bridge element to correspond to the four environmental categories.

Table 1: Environmental Conditions Included in Pontis for Deterioration Modeling

Condition	Description and Impact
Benign	No environmental conditions affecting deterioration
Low	Environmental conditions create no adverse impacts, or are mitigated bay past non-maintenance actions or highly effective protective systems
Moderate	Typical level of environmental influence on deterioration
Severe	Environmental factors contribute to rapid deterioration. protective systems are not in place or are ineffective

In OBMS, the deterioration model acts in a similar manner compared to Pontis. The Markov-chain model is used for performance prediction for different bridge elements. Transition probabilities differ according to the taken MR&R action. However, OBMS do not recognize different environmental conditions. This leads to having future conditions calculated based on the average network deterioration model for the entire network. This might be acceptable for a network level planning. However, special conditions acting on specific bridge(s) within the network will have a different impact on it. For example, severe environmental condition freeze and thaw cycles may act on a certain bridge and expedite the rate of its elements deterioration. This problem is solved by introducing modification factors that relates the average deterioration calculated for the entire network to the specific element deterioration under its special conditions.

3.3 Cost Module

The cost module of a BMS is responsible for calculating costs of different feasible actions that can be performed for maintaining, rehabilitating and/or replacing a certain bridge element. These costs associated with possible actions affected by the element condition state and the severity of the acting environment. Pontis cost module consists of unit costs required for different MR&R actions, and a cost index table to adjust the unit costs according to inflation rates. This is achieved through a time flag associated with unit cost for every action which adjusts the cost according to the expected inflation rates for every specified activity. Finally, a user cost is included in the Pontis cost module, this includes detour cost per hour and km, and the average accident cost. Detour cost per hour accounts for the user cost of a certain detour for a time span of one hour, while the detour cost per km includes the cost of using a detour of length 1 km by a certain vehicle. These detours are constructed due to a certain problem existing in the usual route or due to a clearance problem. While the accident average rate counts for rerouting traffic and probable traffic delays which may results from the existence of geometrical problems, or any other deficiency within the bridge that leads to the occurrence of accidents.

Pricing of a certain action is affected by data existing in several modules within the BMS. These modules are the database modules, the cost module, and finally the project module. Final pricing is achieved by multiplying the element type and the number of unit (ex. square meters of painting) stored in the database module by the unit cost of accomplishing the required activity stored in the cost module (unit price of painting a square meter of the element). The obtained cost is supplemented by the indirect cost through the project planning module. The indirect cost includes cost for site mobilization, traffic control, and administrative costs. The direct and indirect costs for different types of actions and implemented activities in a bridge network are introduced by an expert elicitation process, in which different parties experience is used for estimating the cost. A different approach for the cost calculation may be selected, where the cost of every action previously taken is used as a guideline for similar actions that could be possibly taken in the future. This approach should consider the inflation rates in the location where the BMS is applied.

The Ontario BMS (OBMS) performs its cost calculations through its cost module that simulates Pontis. The OBMS has its database for item pricing similar to a tender document, where element various pricing for replacement, maintenance and/or repair are introduced by contractors. Average pricing for every item is added according to the item condition, total pricing can be calculated for the required MR&R technique.

3.4 Optimization Module

The optimization module generates the main output of the BMS, which is the set of preservation and improvement actions required for the bridge network in each year of the planning horizon. Preservation action usually includes do-nothing, repair, rehabilitate, and replace. Improvement actions usually include deck widening and superstructure raising. Optimization is a complex process that depends on visual inspection data, inventory data, deterioration models, and cost models. The Markov-chain stochastic model is used for predicting the future condition of bridge elements in different environments when various maintenance actions are implemented. Linear, non-linear, and integer programming are the most common techniques used for maintenance optimization. The unit cost and benefit associated with each action are obtained from the cost module, while maintenance policies, improvement standards, and budget constraints are entered by the agency through the optimization module.

Two optimization approaches, shown in figure 3, are generally adopted in BMSs: 1) bottom-up approach; and 2) top-down approach. Pontis and OBMS use the top-down approach where budget constraints and agency standards are utilized to specify general policies which are applied by optimization module for selecting the maintenance projects to be performed at the network level. Other BMSs uses the bottom-up approach, where the standards required for different bridge elements mandates several maintenance projects. The cost of these projects is compared to the available budget, and several iterations are performed till the best set of projects is determined.

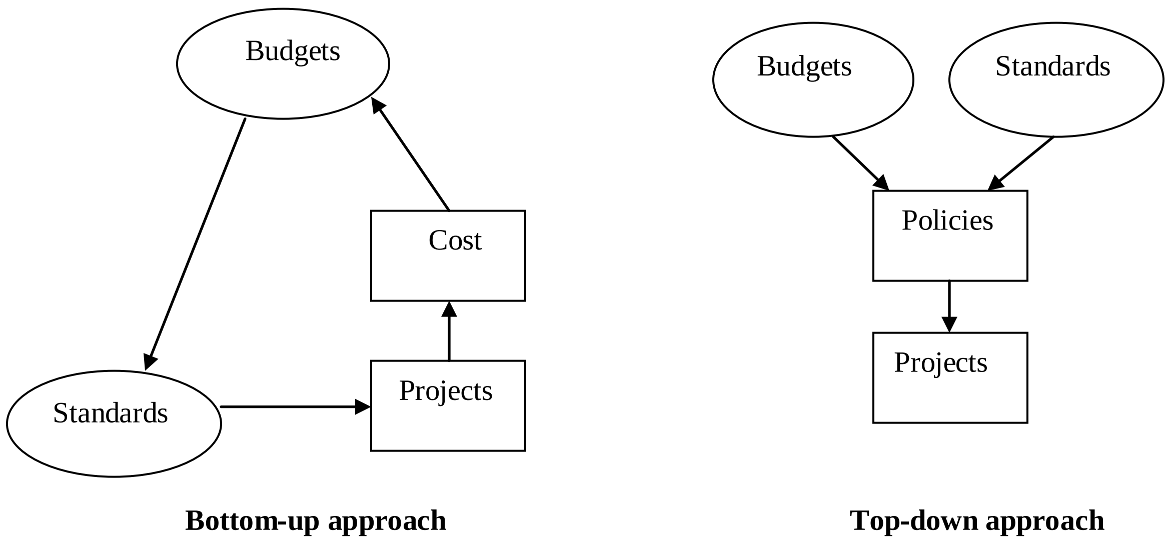

Figure 3: Alternative Markovian Approach for Different BMSs

For Pontis, when a budget constraint is applied, preservation plans will be optimized for all bridges within the network. The cost of recommended actions is calculated. These are defined as preservation needs for the entire network. The portion of needs which can be met in one fiscal year is defined as programmed work. Other projects exceeding the available budget limit is defined as backlog which can never be accomplished due to funding shortage.

4. Users' Comments

As previously stated, the Pontis BMS is the dominant system in the United States of America, beside being adopted in several countries worldwide. It is found that the majority of the Pontis users depend on the inspection and data modules within the BMS. This entitles them to use Pontis as a sufficient database for recording the history of the inspections, in addition to the on-going inspections performed on a biennial basis. Agencies using Pontis as a database for their work regularly modify their inspection techniques and level of inspection to suit the element classification in the Pontis.

Other state DOTs tailor the Pontis BMS by adding their own elements, introduce their state related factors affecting the bridge deterioration and pricing for maintenance and rehabilitation plans. Telephone conversations were performed to review the users' comments on the Pontis implementation in their agencies. This covered the level of using Pontis, modifications required for adopting Pontis, and the results of implementing Pontis in optimization and preservation. The results of the survey are shown as follows:

4.1 South Carolina Department of Transportation (SCDOT)

The South Carolina Department of Transportation owns and operates more than 8,000 structures. There were no formal procedures adopted by the State DOT for inspecting the state bridges, or planning the maintenance, rehabilitation, and replacement (MR&R) for the bridge networks.

Manual inspections and personal judgment was utilized in SCDOT till the year 1995, after which Pontis was first implemented. Only 2000 bridges were used as a bridge network within Pontis (this represent 25% of the total number of structures under the SCDOT supervision). The total number of bridges recommended for replacement by Pontis was 498; this exceeded the available budget for maintenance and rehabilitation purposes at the SCDOT. These 498 bridges were short listed to 35 bridges only according to the priority of MR&R plans required for the network. Personal judgment for the same bridge network included 31 bridges of the 35 recommended bridges. This means 88% of similarity between the manual planning and Pontis implementation results.

4.2 New Jersey Turnpike Authority (NJTA)

The New Jersey Turnpike Authority implemented the Pontis BMS for several years starting from the year 1997 to year 2002. It was implemented in parallel to the personal planning for comparing results. Pontis was tailored to match the needs of the NJTA. Tailoring of pontis included the addition of unit prices that matches the average construction activities prices in the State of New Jersey. Manual planning was conducted and results were checked versus the Pontis preservation and optimization plans.

The Obtained results from Pontis and manual planning have a high percentage of similarity for the NJTA database which includes 500 bridges. However, the implementation of Pontis was terminated by the year 2003. This decision was related to several non-technical factors. Mainly, the inability of training a large number of inspector for collecting data in the way required by Pontis, the inability of having a suitable number of staff to change Pontis modules to match the prevailing conditions, in addition to the high annual licensure costs. These problems were increased upon the unity of the New Jersey Turnpike Authority (NJTA) and the Garden State Parkway creating a larger bridge network of 1000 bridges, which doubled the size of the inventory and required the coverage of remote places.

4.3 Kansas Department of Transportation (KDOT)

Kansas Department of Transportation (KDOT) was among the first state DOTs implementing the Pontis as a management system for their bridge network. Pontis implementation at KDOT started in July 1992. However, KDOT is depending on Pontis as a database for recording the results of their previous inspections, and as a calendar for the future requested inspections. KDOT utilizes the AASHTO CoRe elements in addition to several added ones to match the types and systems of bridges constructed in the State of Kansas, as the unpainted bottom chord deck truss (element 132), reinforced concrete culvert wing (element 244), concrete hinge (element 345) and concrete girder ends (element 346). The utilization of other Pontis module as optimization and cost modules are under consideration. However, the preparation of a staff that can completely tailor different Pontis modules represents the main obstacle for this step.

4.4 Nebraska Department of Roads (NDOR)

Nebraska Department of Roads started to develop their own criteria for assessing bridge conditions in order to implement the bridge management system software (Pontis) as a decision making tool. NDOR will use Pontis as a database prior to using the decision making modules for prioritizing their bridge maintenance decisions.

5. Summary

Several BMSs are being adopted by the States Departments of Transportation and Highway Authorities. Pontis represents the dominant BMS in the United States of America. Ontario started its own BMS which is applied on a provincial level in Canada. Though the Ontario BMS appeared as a different system which is not correlated to Pontis. The two systems have the same modules. They adopt element level inspection; the standard element database in both systems can be tailored to match the type of bridge and the level of the user inspection according to the different agencies using the BMS, Markovian top-down stochastic modeling is utilized for defining the future condition of every bridge element within the two systems. Expert judgment may be used in future predictions and adjusting cost modules in both BMSs to match the environment conditions and/or the average pricing of different activities on a certain area or a certain bridge network.

Different agencies adopting Pontis in the United States do not have the same level of system implementation. These varied from having Pontis used as a database for their bridge network. Its general information as address, system of construction and geotechnical properties, in addition to recording the results of inspections (usually done in a biennial basis). This typically exists in the State of Kansas, to using the deterioration, optimization, and cost modules for predicting the future status of a bridge element after undergoing the proposed preservation plans. This advanced degree of Pontis implementation exists in several states including North Carolina and California. These selected preservation plans are indentified for a certain bridge network among an infinite number of plan possibilities according to the budget constraints and required standards for the bridge network.

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