The Pontis Bridge Management System

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Summary

The Pontis bridge management system is the predominant bridge management system employed in the United States. The system employs a network optimization model for preservation, formulated as a Markov decision process with a linear program solution procedure. On each bridge, a set of level-of-service standards determines functional needs, whose benefits are calculated according to a user cost model. A multi-year program simulation generates project alternatives by combining preservation and improvement needs on each bridge. The program is optimized within budget constraints by means of an incremental benefit/cost algorithm.

The mathematical formulation of each of these components is presented and discussed. Aspects of system development and data management are outlined, along with the current implementation status. California's experience with the use of Pontis in its funding process is highlighted.

Background

Through the 1960s and into the 1970s, bridge maintenance, repair and rehabilitation (MR&R) activities were performed on an "as-needed" basis. Owning agencies, when alerted to situations warranting attention, employed the best practices of the day to remedy problem areas. This responsive approach appeared to sufficiently address potential safety issues. This changed in the late 1960s, when a series of bridge failures focused public attention on deterioration of the existing bridge inventory, motivating the US federal government to mandate standardized bridge inspection procedures. Data collected through this inspection process formed the basis for bridge management in the US from the 1970s and into the 1990s.

In the mid-1980s, individual states came to recognize the mounting problems of bridge maintenance needs, the potential for information technology to help in securing maintenance funding, and the promise of systems analysis tools for optimization of scarce financial resources. Several states, notably Wisconsin, Pennsylvania, and North Carolina, began the development of improved inspection procedures and analytical methods to assist in their own decision making [1].

Recognizing a high level of interest among the states, the Federal Highway Administration (FHWA) initiated Demonstration Project 71 (DP-71) to examine the current state-of-the-practice in bridge management and to identify tools and technologies available for bridge management decision support. Out of this effort, the FHWA, in cooperation with state DOTs, pursued the development of a generic Bridge Management System (BMS) suitable for national implementation. This led to the development of the Pontis system.

System Objectives

Pontis is both a software system and an organizing framework to help bridge managers make the transition from collecting and processing raw safety inspection data to a more sophisticated approach of optimizing the economic efficiency of the bridge network. In today's complex political and financial environment, the system provides a defensible and understandable means of expressing the long-term benefits of keeping bridges in good condition, as well as an objective way of choosing among maintenance, improvement, and replacement opportunities. In order to succeed in this objective, Pontis has the capacity to express the engineering concerns of deterioration and structural performance in economic terms understandable to a broader audience.

Computational Platform

The success of Pontis in accomplishing these objectives depends, in part, on harnessing the power of modern database management and graphical user interfaces. Pontis operates in Windows 3.1, Windows 95, or Windows NT using a combination of Sybase Powerbuilder 5, for the user interface and database management tasks, and Microsoft Visual C++ for the analytical functions. Pontis directly supports four commercial database management systems, Oracle 7, Sybase SQL Anywhere 5, Microsoft Access 2.0 and Access 97. In the future, additional database platforms may be supported depending on agency demand.

All database management functions utilize Microsoft Open Data Base Connectivity (ODBC), enabling Pontis users to employ different database technologies in different parts of their organizations. This addresses remote database entry issues and provides scalability. Built-in database exchange functions allow an agency to collect inspection data in the field and upload it to a corporate database for multi-user, centralized access to bridge information.

Peer-reviewed by international experts and accepted by the IABSE Publications Committee

As a database-centered system, Pontis has an extensive set of data items, including those that are necessary to support the National Bridge Inventory as well as data that contribute to analytical procedures and decision support. SQL ("structured query language") and simplified graphical query capabilities are available through InfoMaker, enabling the user to manage information and produce customized reports and forms.

Components of Pontis are organized into a series of modules reflecting different bridge management activities. In object-oriented analysis terms, these are referred to as "use cases," which are evident in the desktop shown in *Fig. 1*. Access to these modules is through a tool bar, menu items, and an active structure list. The Pontis structure list can coordinate with user defined bridge "applets" or micro-applications to provide additional bridge management functionality to address specific agency needs. Since the user agencies differ greatly in their bridge management requirements and procedures, the ability to customize and expand the system is very important to its acceptance.

Pontis Analysis

The analysis includes a network-level preservation model for maintenance, repair and rehabilitation, a functional improvement model, and a program optimization model. Each of these components is described separately below.

Preservation Model

The Pontis preservation model is formulated using a top-down analytical framework. The optimization develops pure network-level policies first, and then uses these results to guide project-level decisions. Since the policy analysis is strictly network-level, it does not consider data on individual bridges. Instead, it analyzes the generic action alternatives that are available to the agency in response to every possible condition state that can be observed on every element present in the inventory.

State	Name	Description
1	No corrosion	No evidence of active corrosion; paint system sound and functioning as intended.
2	Paint distress	Little or no active corrosion. Surface or freckled rust has formed or is forming.
3	Rust formation	Surface or freckled rust is prevalent. There may be exposed metal but no active corrosion.
4	Active corrosion	Corrosion present but any section loss resulting from active corrosion does not yet warrant structural analysis.
5	Section loss	Corrosion has caused section loss sufficient to warrant structural analysis to ascertain the effect of the damage.

Table 1: Condition state definitions for element 107, painted steel open girders

Inspection Data

To support the data requirements of Pontis, inspectors record the condition of each element of each bridge, usually on a biennial cycle. There are approximately 120 basic elements, or Commonly Recognized (CoRe) elements, pre-defined in Pontis. The CoRe elements provide standardization of inspections and data models by bridge-owning agencies, thus facilitating the exchange of information. Additional elements may be added by individual agencies as required.

Elements are characterized by discrete condition states, which describe the type and severity of element deterioration in visual terms. As an example, the condition state language for element 107, painted steel open girders, is shown in *Table 1*. Inspectors record the percentage or quantity of each element found to occur in each condition state.

Pontis includes a translator function to convert the element inspection results into the older 0-9 rating scale for deck, superstructure, and substructure. Although these older assessments are not used in the Pontis analysis, they are still required by the US federal government as a means of summarizing the condition of each bridge for the National Bridge Inventory (NBI).

Deterioration, Action Effectiveness and Action Cost Models

Pontis uses a Markovian deterioration model to predict the probability of transitions among condition states each year. Since the number of condition states is limited to five for each element, the transition probability matrix is very small. Markov models assume that the condition states them-

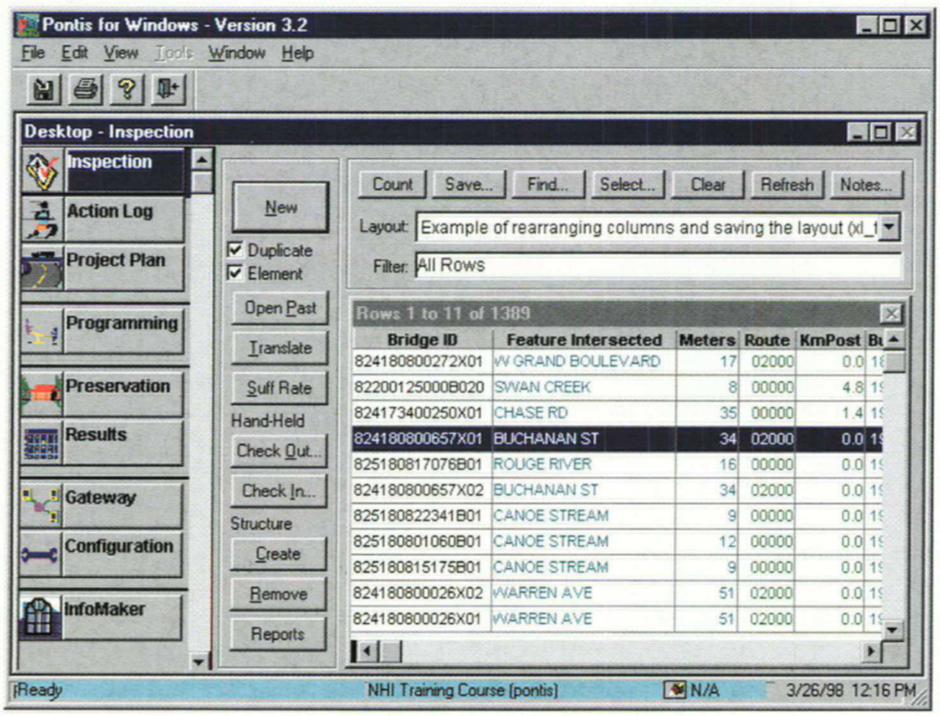

Fig. 1: The main Pontis desktop screen

selves incorporate all the information necessary to predict future deterioration. Thus, condition predictions for any future year can be made simply by matrix multiplication.

Fig. 2 shows an example of a Markovian prediction over a 20-year period. The blue circles indicate state probabilities, which can be interpreted as the percentage of the inventory predicted to be in each state. The arrows represent transition probabilities.

For each condition state, available actions and associated costs are defined, as shown for element 107 in *Table 2.* The information presented in this example is taken from actual data used in the model by the California Department of Transportation (Caltrans). Up to three actions, inclusive of the do-nothing "action", may be defined for each condition state of each element. The do-nothing action represents the deterioration model. If actions 1 or 2 are taken, there is an improvement in condition state, also represented by transition probabilities, and a cost is incurred. Failure costs are defined for each element and failure probabilities from the last condition state are determined. For the example in *Table 2,* these values are USD 7000 per unit and 9.45% respectively.

In order to model some of the variation of deterioration and costs within a state, Pontis allows the elements on each bridge to be classified in up to four categories of environments. Each environment for an element can have its own deterioration and cost models.

Preservation Optimization – Network Level

Network optimization in Pontis is performed at the level of generic elements. The fundamentals of discounted dynamic programming are used to find the optimal, long-term policy that minimizes expected life-cycle costs while keeping the element out of risk of failure.

The objective function seeks to determine the optimal policy, where a policy is defined as a rule for the selection of the appropriate action. Assuming stationary policies, the condition state distributions of the element at sequential periods of observation form a Markov chain. The optimality equation is the expected life-cycle cost, given the assumptions specified and bounded action costs, shown as follows:

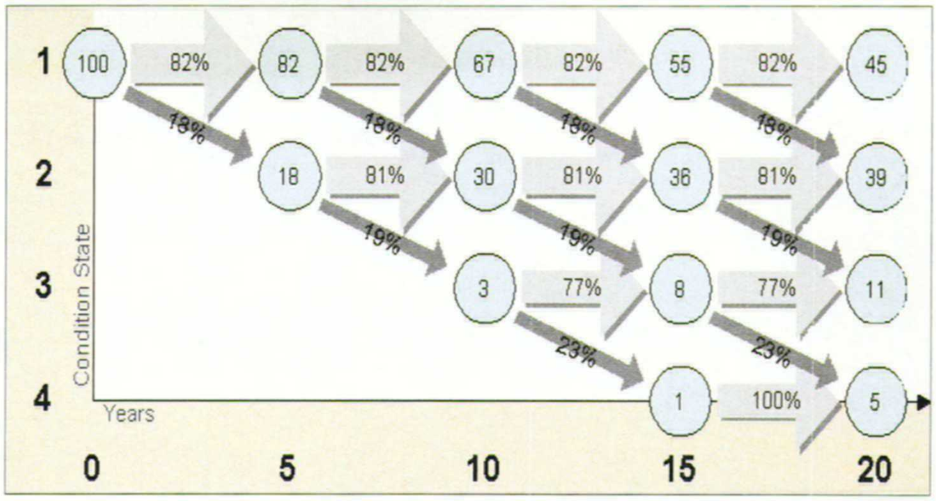

Fig. 2: Example of a Markovian deterioration model

$$V(i) = \left[C(i,a) + \alpha \sum_j P_{ij}(a) V(j) \right]$$

where

i = condition state observed today

j = condition state predicted to occur one year in the future

$V(i)$ = long-term cost expected as a result of being in state i today

$C(i,a)$ = initial cost of action a taken in state i

α = discount factor for a cost incurred one year in the future

$P_{ij}(a)$ = transition probability of state j conditional on state i and action a

$V(j)$ = long-term cost expected as of next year if state j occurs.

Thus, the long-term cost is simply the sum of the initial action cost and the discounted sum of the future long-term costs of each possible condition state which may result in the following year. The optimality equation thus takes a recursive form through which the network-level model seeks the set of actions which minimize the long-term costs for each condition state. The combination of the minimum cost actions forms the optimal policy for a given element in a given environment.

There are a variety of ways to solve this type of Markovian decision process. Approximation techniques available include policy improvement algorithms and the method of successive approximations, both of which are described in a variety of texts on systems analysis and Markov decision processes. The problem may also be transformed to enable solution using linear programming. This approach is taken in Pontis.

After the optimal policy is determined, a dual form of this model is solved using simultaneous equations to find the steady-state condition state distribu-

State	Actions	Transition probabilities (to State)					Cost/Unit (USD)
		1	2	3	4	5	
1	0 – Do nothing	93.81	6.19	0	0	0	–
	1 – Surface clean	100	0	0	0	0	62.34
2	0 – Do nothing	0	88.88	11.12	0	0	–
	1 – Surface clean	1.00	99.00	0	0	0	80.84
	2 – Surface clean & repaint	96.00	4.00	0	0	0	225.26
3	0 – Do nothing	0	0	87.12	12.82	0	–
	1 – Spot blast, clean & repaint	88.00	12.00	0	0	0	328.48
4	0 – Do nothing	0	0	0	88.88	11.12	–
	1 – Spot blast, clean & repaint	61.00	14.00	5.00	20.00	0	455.90
	2 – Replace paint system	97.00	3.00	0	0	0	396.32
5	0 – Do nothing	0	0	0	0	90.55	–
	1 – Major rehab	30.00	9.00	1.00	20.00	40.00	1279.52
	2 – Replace unit	100	0	0	0	0	2394.82

Table 2: Transition probabilities and action USD costs for element 107

tion which would be achieved if the optimal policy were followed for a sufficiently long period of time.

Improvement Model

In Pontis, functional improvements are considered separately from preservation. The model relies upon the definition of minimum level-of-service standards, used to assess needs; and design standards, used to assess the amount of work required to correct existing deficiencies. The user may vary the level of service criteria by traffic volume class, functional classification, bridge ownership, and national highway system designation. Additionally, the user may specify feasibility criteria for improvement actions.

Improvement needs are determined by comparison of the level-of-service standards with the physical characteristics of each bridge. Based on the design standards and a unit cost matrix, the functional improvement costs are calculated.

Benefits of functional improvements in Pontis are assessed in terms of user cost savings. When a deficient NBI approach alignment rating or travel way width exists on a bridge, road users are theoretically subject to higher accident risk. To evaluate a functional improvement or replacement to correct the deficiency, the user cost model predicts a reduction in accident risk, which then is multiplied by an accident cost to yield a user cost savings. When a bridge has substandard vertical clearance or load capacity, certain trucks are unable to pass on or under the bridge and must detour, thus incurring higher labor costs and vehicle operating costs. The user cost model estimates the volume of detoured traffic and the resulting user cost, which would be avoided if the deficiency were corrected. The total user benefit of a project is therefore:

$$B = W(B_a + B_v + B_t)$$

where

W = weight given to user cost, a matter of agency policy
B_a = savings in accident costs
B_v = savings in vehicle operating costs
B_t = savings in travel time costs

The method for estimating accident user cost savings in Pontis is derived from the North Carolina Bridge Management System, using the following formula:

$$B_a = 365 \times V(R - R')C_a$$

where

V = forecast average daily traffic on the bridge roadway
R = estimate of the current accident risk per vehicle
R' = estimate of the accident risk per vehicle after improvement
C_a = average cost per accident

Based on North Carolina research, an approximate way to estimate R based on bridge attributes is given as follows:

$$R = 200 \times 0.3048W^{-6.5}[1 + 0.5^{\frac{(9-A)}{7}}]$$

where

W = roadway width curb-to-curb (m)
A = approach alignment rating (typically 2–9)

R' is estimated in the same way for the roadway characteristics after the improvement.

For bridges having impaired vertical clearance or load rating, Pontis calculates the vehicle operating cost associated with traffic on a detour route, and assumes that this entire cost is saved if a functional improvement is undertaken. Only trucks are assumed to be affected. The project benefit in terms of vehicle operating cost benefits is then:

$$B_v = 365 \times V_D \times C_v \times D$$

where

V_D = number of trucks detoured each day at the bridge
C_v = average vehicle operating cost per km of detour
D = detour distance for the bridge roadway in km

The number of trucks detoured V_D is used in both the vehicle operating cost model and the travel time cost model. It is calculated based on the distribution of trucks of different heights and weights in the traffic stream.

Pontis calculates the travel time cost associated with traffic on a detour route, in a manner similar to vehicle operating cost. Again, only trucks are affected. The project benefit in terms of travel cost savings is:

$$B_t = 365 \times V_D \times C_t \times \frac{D}{S}$$

where

V_D = number of trucks detoured each day at the bridge
C_t = average travel time cost per hour of detour
C_t = detour distance for the bridge roadway in km
S = speed on the detour route (km/h)

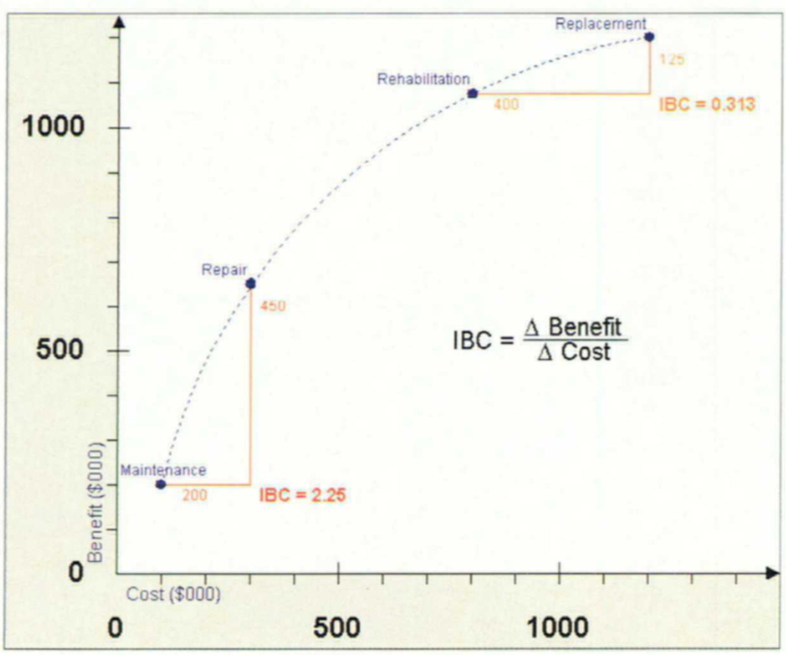

Fig. 3: Diminishing marginal returns

Project-Level Programming

When each bridge in the inventory is inspected, the actual condition states of each element on the bridge are observed. Pontis consults the network optimization results to find the recommended maintenance, repair or rehabilitation (MR&R) action with its unit cost and benefit for each observed condition state. The difference in long-term costs between the optimal action and the do-nothing action is considered the net benefit of that action; thus a large net benefit implies a strong recommendation. Summation of costs and benefits over all elements for each bridge provides an estimate of the total MR&R needs, and associated benefits of taking action, for each structure in the inventory.

The preservation needs may then be combined with the improvement needs. In cases where a bridge has both MR&R needs and functional deficiencies, it may be considered for replacement. Replacement may be triggered if the appropriate functional improvement action is not feasible, if the combined MR&R and improvement cost exceeds a certain fraction of the replacement cost, or if replacement provides a more attractive benefit/cost ratio.

Maintenance, repair and rehabilitation cost estimates are based entirely on network-level considerations and do not consider site-specific factors. This leads to a lack of precision due to indirect cost items such as traffic control and mobilization. Pontis enables the user to calculate site-specific costs for a project and to include these in the project programming phase.

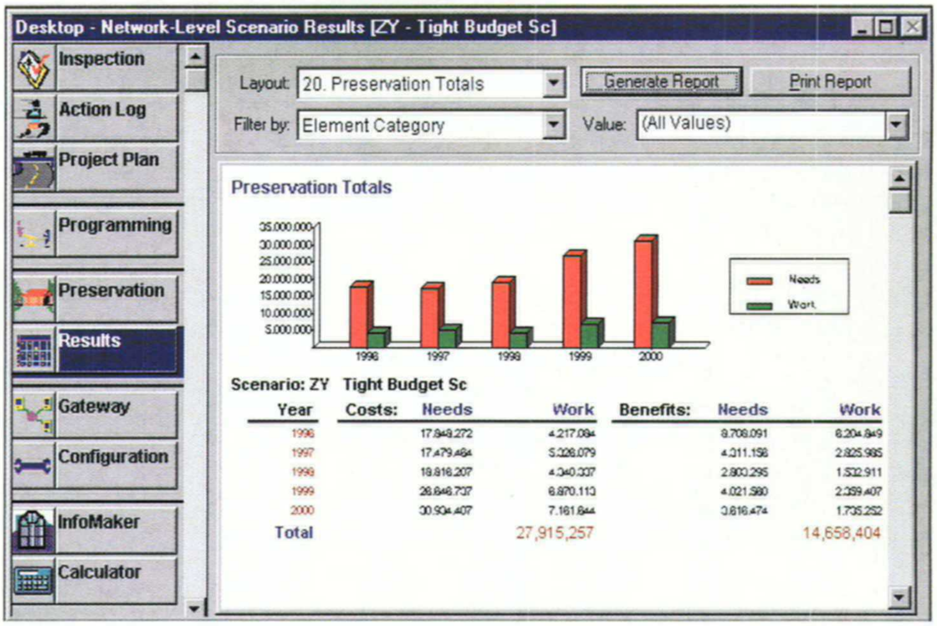

Fig. 4: Screen output of network-level results

The final decision as to whether to proceed with each project depends on funding constraints and the relationships among competing project alternatives. Since there is almost never enough funding to address all needs, an objective means is required to find the program of projects which maximizes the benefit achievable within a constrained budget. Pontis uses an incremental benefit/cost method to do this.

Incremental benefit/cost analysis may be best understood within the context of zero-based budgeting. The procedure starts with a zero budget, thus requiring every bridge to choose its do-nothing alternative, with zero cost and benefit. As a small increment of funding is added to the budget, it is allocated to the bridge that is able to maximize the marginal return, the increase in benefit achievable for a given increase in cost.

Fig. 3 shows the typical pattern of benefits and costs for mutually exclusive alternatives on a bridge. Alternatives that are below the concave-downward line on the graph exhibit a lower incremental benefit/cost ratio than competing uses of the funding, so they are eliminated from consideration. This leaves a pattern of diminishing marginal returns for successive increases in costs. Each time a new increment of funding is added to the program, it is optimally allocated to the bridge and the alternative that offer the steepest increase in benefits. Addition of further increments of funding is continued until the budget constraint is reached.

Although the program optimization in Pontis is structured like an integer program with discrete project alternatives, the mutual exclusivity of alternatives and the pattern of diminishing marginal returns allow the formulation to be solved using a very efficient gradient method, producing nearly optimal results.

Outputs and Reporting Capabilities

Optimization results, project planning and bridge programming information, and historical information are maintained in the Pontis database. The information may be extracted and presented in a variety of ways. Results may be viewed on-screen in the Pontis system, as shown in *Fig. 4,* which depicts the escalation of needs over time in an under-funded program. A large set of predefined reports is also available to extract useful information. User generated reports may be created through InfoMaker, or alternatively, standard SQL macro language scripts may be used to extract additional information. SQL scripts are applied using the database vendor's SQL interpreter system outside the Pontis environment. Internally, Pontis also offers a basic formula processing language, a flexible means for automatically generating or updating information in the database.

Evolution and Current Implementation Status

In the two years following the initial release of Pontis 1.0 in 1992, the original Pontis user group of five states quickly expanded. Seeking a stable long-term mechanism to support and enhance Pontis on behalf of a larger number of states, the FHWA granted the responsibility for Pontis to the American Association of State Highway and Transportation Officials (AASHTO).

In 1994, AASHTO received financial support from 38 US states to further enhance the system and provide ongoing assistance to the users in its maintenance and implementation. Today, 44 agencies in three countries have licensed Pontis release 3.2 [2] from AASHTO. The licensees include 39 states, two counties, one city, and national highway agencies in Kuwait and Hungary. More than 75 percent of the licensees have been performing Pontis element inspections for more than two years and, thus, given the mandated NBIS two-year inspection cycle, have complete coverage of their inventories. Some of the more advanced states, such as California and Minnesota, have up to six years of experience with the Pontis analytical procedures. These agencies have begun to apply Pontis for long-range planning and budgeting, including the use of Pontis reports in the procurement of maintenance funding from their state legislatures.

California's case is a good example of a more advanced implementation stage. The California Department of Transportation (Caltrans) began its Bridge Management System (BMS) implementation with the introduction of element inspection techniques in late 1991. By late 1994, Caltrans engineers were collecting element inspection information for all bridges in the state during routine inspections.

In June of 1996, the Caltrans Bridge Management Summary report was presented to the California Transportation Commission. This report represented the first formal presentation of simulated needs and network health as developed by Pontis. The information from Pontis and other sources presented in the Bridge Management Summary report was effective in convincing the Commission to increase funding for bridge repair and rehabilitation. The presentation of bridge needs from Pontis and other BMS tools has resulted in recommended funding for bridge repair and rehabilitation of 99, 105, 140, 175 and 213 million USD respectively for a five-year period beginning with the 1998/99 fiscal funding year. These funding levels represent an average year over year increase of 25 percent for bridge repair and rehabilitation in California.

The health index values generated during the deterioration simulation process have been a particularly effective means of communicating bridge needs in California. The health index is a 0–100 number representing the remaining economic value of a bridge. A bridge with a health index of 0 has no remaining value, while a bridge with a value of 100 retains its full worth. Element inspection quantities, condition distribution and element failure costs are used to develop a number reflecting the current "health" of a single bridge or a network of bridges. The health index works in conjunction with the program simulation process to record the condition of all bridges and the network after selecting optimal projects using the available budget for each year. This budget based health index provides a way for bridge managers to forecast and clearly present the structural condition of a network of bridges based on specific future budgets.

As bridge managers become more familiar with the concepts of bridge management, the use of Pontis is being expanded to areas other than forecasting network funding needs. Recently, the Pontis program has been used to aid in the structure type selection process. The optimal network solution of the deterioration model within Pontis was used to forecast expected maintenance costs for six alternative replacement structure types proposed for a 1000-m-long crossing over the Carquinez Straits in California. By developing network models that represented site-specific deterioration and costs for each proposed alternative, the optimal solution to the models represented the optimal maintenance strategy for each of the structure types. This innovative application of the Pontis software made it possible to calculate the expected annual maintenance costs for each proposed structure type. The maintenance cost comparisons were combined with initial construction cost estimates to produce true life-cycle cost estimates for consideration in the ultimate structure selection.

Conclusions

Pontis represents an ongoing effort to ensure the long-term serviceability of the bridge inventory through objective analysis of inspection data and rigorous application of engineering economics. Because of the marriage of engineering and economic models, the system is able to analyze the life-cycle implications of decisions and express the results in a form understandable to a broad audience, including managers and legislators. Through continuous support and enhancement of Pontis, AASHTO intends to keep advancing the state-of-the-art in bridge management.

References

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