TOOLS FOR BRIDGE MANAGEMENT DATA ANALYSIS

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ABSTRACT

The objective of bridge management is to allocate and use the limited resources in an optimal way for the provision of service. Data collection and data analysis are essential components of a bridge management process. Without these two activities, strategy selection and implementation cannot function efficiently. Data collection and analysis are therefore conducted not for their own sake, but to enable the other activities in the process to be well executed. An important purpose of data analysis is the prediction of the impact of different strategies on the system objectives. This involves predicting future conditions of bridge elements, agency costs of different projects and activities, and user and nonuser consequences expressed as user costs, user time, accident rates and other impacts. In this paper the application of several data analysis techniques, such as regression analysis, Markov chains, Bayesian estimation and fuzzy set theory for the prediction of bridge element condition, agency costs and user costs, is discussed. Whatever techniques are used, the point is stressed that the success of data analysis depends ultimately on the quality and sufficiency of data gathered. The objective of data analysis is not the analysis but better strategy selection. To assist in strategy development, several prioritization and optimization procedures exist that can be usefully applied. Some common techniques for priority setting and optimization, such as the analytic hierarchy process, linear and integer linear programming, dynamic programming and network techniques, are briefly discussed.

INTRODUCTION

The central role played by data and data analysis in bridge management is clear—without them the bridge management process would be not much more than ad-hoc reactions to the most urgent crises, in stead of a well-planned, pro-active process. It is also true that data collection and data analysis are not objectives in themselves. These activities should always be conducted with a clear view of the ultimate objectives of the bridge management process. Some purposes of data collection and data analysis are as follows:

- Provide an inventory of bridges, bridge elements, traffic volumes and other characteristics of the system.
- Reflect the current condition of bridge elements.
- Provide a record of implemented maintenance, rehabilitation and replacement actions, and their associated impacts and costs.
- Enable deterioration prediction—the forecasting of the future condition of bridge elements.
- Predict the impacts of different alternatives.
- Estimate the costs associated with different alternatives—for the agency, users and nonusers.
- Enable the evaluation of different alternatives for a bridge—project level analysis.
- Optimize allocation and use of resources on a network-wide basis—network level analysis.

Data needs and collection practice for bridge management systems are discussed in the paper by Turner and Richardson (*1*). The present paper discusses several analysis techniques that can be used to achieve the above objectives.

CONDITION DATA ANALYSIS

Current Condition

Current condition can be represented several ways. One of the most common methods is to construct condition indices, which aggregate data of the conditions of individual bridge elements to obtain indices for larger elements, such as a deck, superstructure or substructure, or for a bridge or a network of bridges. The level of aggregation will be determined by the purpose of the index, especially the intended users or audience.

Condition Prediction and Remaining Life

Regression Models

Regression analysis is applied in many areas of bridge management systems. Equations are estimated to predict the future conditions of bridge elements as a function of the current condition, the age of the element, material types, maintenance practices, environmental conditions and deicing chemical use, traffic volume, and rehabilitation action taken. These predicted conditions are then used to estimate future agency and user costs, to evaluate different rehabilitation and replacement alternatives, to choose strategies under budget and other constraints, to predict the impacts of different budgets, and to plan work over the medium and longer term. The collection of the necessary data such as current condition and maintenance actions, to make these forecasts is discussed in the paper by Turner and Richardson (*1*). Examples of regression models of bridge deck, superstructure and substructure deterioration can be found in the Indiana Bridge Management System (IBMS) (*2,3*). Agency and user costs also can be predicted with regression equations. This is discussed in Life Cycle Cost Analysis Section of this paper, and in the paper by Johnston, et. al. (*4*).

A commonly used form of equation in regression analysis, due to the ease with which the parameters of such an equation can be estimated, is the linear regression equation. A linear regression equation can be stated as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \epsilon$$

where,

Y ≡ dependent variable
X_j ≡ independent or explanatory variable; $j = 1,2,...,k$
β_j ≡ unknown parameter to be estimated; $j = 1,2,...,k$
ϵ ≡ random error term

The dependent variable might be the future condition of a bridge component, and independent variables might include the current condition, time since the previous major rehabilitation, the type of rehabilitation implemented, material type and environmental conditions. The random error term ϵ is included since the equation will never be a perfect representation of the underlying phenomenon. Certain statistical assumptions are made regarding these random errors. If these assumptions are violated, poor models might be obtained.

An important issue is the specification of the functional form of the regression equation. Unfortunately, there are no statistical recipes available to accomplish this. On the contrary, trying out many functional specifications and then choosing one solely based on goodness-of-fit or any other statistical measure, is strongly discouraged. Specification of the functional form should be based on a deeper understanding of the underlying principles governing the performance of the system. Only then is there any assurances that a regression model, that fitted a particular set of data well, will provide good predictions based on different values of the independent variables. This is especially true if the regression model is used for extrapolation, as is usually the case in bridge management systems.

Different methods can be used to obtain parameter estimates that will make the equations fit the data as well as possible. The simplest and most common method is ordinary least squares. A more versatile method is maximum likelihood. The "goodness-of-fit" of the regression model can be evaluated in different ways. The most popular is the coefficient of determination, R^2, which measures the closeness of the equation to the data. As a single measure it has limited value. Most real-world systems cannot usefully be modeled with a single equation. Realistic regression models are therefore often systems of simultaneous equations. Techniques for the estimation of simultaneous equation systems, such as two-stage least squares are discussed in the literature. Additional issues such as the identification problem, arise with the estimation of simultaneous equation systems which have to be resolved before all parameters can be estimated.

Markov Chains

If the conditions of bridge elements are classified into discrete states, for example condition index represented by the numbers one to nine, then the deterioration process can be modeled as a Markov chain. The state of each element or the proportion of elements in each state can be measured during an inspection. A Markov chain describes a process that undergoes transitions from a state at one stage to a state at the next stage. Transitions are usually regarded as probabilistic events, with associated transition probabilities, represented by a transition matrix. A transition probability can be interpreted as either the probability that a single element will undergo a specific transition or the long-run proportion of elements that will undergo the transition.

An underlying assumption of Markov chains is that given the present state of the process, the future states are independent of the past. This assumption might not be satisfied if the state of an element is defined based on the condition of the element only. This is because the probabilities of deterioration, and therefore transition probabilities, will not be influenced only by the current condition of the element but also by such factors as age of the element, past rehabilitation of the element, the conditions of other elements, and the external forces such as traffic load applied. To make better use of Markov chains for condition prediction, the states of an element therefore have to be defined based the element's current condition and on the factors that have a significant influence on its deterioration.

This might cause the number of possible states of each element to become very large. For example, with three factors, such as current condition, level of maintenance and traffic load, each with five levels, the element has 5 x 5 x 5 = 125 possible states. If transition probabilities P_{ij} from each state i to each other state j have to be estimated, then 125 x 125 = 15,625 transition probabilities have to be estimated. If this has to be done for each type of bridge, and each set of environmental conditions, then this approach is not very practical. Fortunately, the problem is not always as severe as this. Many transition probabilities can be assumed to be zero (0). To make provision for changing transition probabilities as an element ages, (to take care of the assumption of time homogeneity), different transition matrices can be used for elements of different ages. Transition probabilities, P_{ij}, have to be estimated. One approach is to estimate regression models having the state as dependent variable, assume a probability distribution for the random error term, and then to convert interval probabilities to transition probabilities. To use a Markov chain, individual states have to be defined as intervals on a continuum. This approach requires a large amount of applicable data which are not yet available at most transportation agencies. Alternative models, such as multinomial logit models, also can be used.

Another approach, suggested by the developers of Pontis, is to use the subjective judgment of bridge maintenance experts to obtain estimates of transition probabilities (*5,6*). As data are collected through regular inspections, these initial estimates are updated and improved. The updating technique draws on the principles of Bayesian estimation.

Bayesian Estimation

Bayesian estimation can be used for updating the estimated probabilities of future conditions. It is particularly well suited for updating the estimates of transition probabilities in Markov chain analysis as additional data become available with inspections. It was incorporated into the Pontis bridge management system (*5,6*).

Under suitable assumptions, the updated estimate (called posterior mean) equals a weighted average of the previous estimate (called prior mean) and the mean of the new data. The weights represent the value attached to the data from which the prior mean was estimated relative to the new data. Usually, the relative numbers of observations are used as weights. If the prior mean was estimated from judgmental methods, then it has to be valued as an equivalent number of observations, representing the amount of data on which the expert's judgment is based. This is the approach suggested by the developers of Pontis (*5,6*). When the estimates are later updated, the posterior values become the prior values for the new estimates. In this way, the effect of initial estimates are reduced as new data become available.

Other Approaches in Condition Analysis Methods

Application of Fuzzy Set Theory Many bridge inspection data items are of a subjective nature. The quality of these subjective data can be improved through better training of bridge inspectors, carefully designed uniform procedures and measures, quality control and quality assurance programs, and better inspection manuals. Such quality assurance procedures were developed for the Pennsylvania Department of Transportation (*7*). An innovative technique to utilize these less exact data items, is the theory of fuzzy sets. Unlike classical set theory where an element is either a member of a set or not, degrees of membership are provided for in fuzzy set theory. A bridge element can, for example, be in both a fair and a poor condition, and to different degrees. This gives a more realistic and flexible method to represent the subjective ratings of bridge elements. The theory of fuzzy sets was applied at Purdue University to assess the condition of bridge components (*8,9*), and to construct a Bridge Safety Index for bridges (*10*).

The Latent Variable Approach in Regression Analysis The approach of latent variables considers the infrastructure "performance" or "condition" as a set of unobservable or latent variables, which depend on other variables such as previous maintenance, environmental conditions and traffic load. The observed characteristics, such as the measured distresses, in turn simultaneously depend on the underlying latent variables. Because variables such as various distresses and structural capacity are measured with a large degree of error, the observed variables can be modeled as functions of the true values as well as stochastic measurement errors. The model also can be enhanced by using lagged variables and by simultaneously modeling deterioration and maintenance. The last option is especially important, because deterioration tends to increase with decreasing maintenance, all other factors held constant. However, maintenance tends to increase with increasing deterioration. If these two relationships are not modeled explicitly and simultaneously, the wrong model might be estimated. This wrong model might very well indicate that deterioration increases as maintenance increases, all other factors held constant, because the model that is estimated might be closer to maintenance as a function of deterioration, than to deterioration as a function of maintenance. These "strange" results have been reported in the literature (*11*).

Latent Markov Decision Process This method explicitly takes the uncertainty (e.g., due to measurement errors) associated with facility inspection into account, and incorporates this into a Markov Decision Process framework. It augments the definition of states to incorporate all information available up to each stage (all previous measured conditions and implemented actions). This causes the state space to grow very rapidly with the number of stages which makes this method computationally very cumbersome. This approach is required to enable the recursive calculation of the conditional probabilities of the actual condition, given all information up to that stage (*12*). With an appropriate cost function based on element condition and implemented action, the strategy selection problem can be formulated in terms of a dynamic program to find the optimal strategy over a finite horizon with no budget constraints (*12*).

LIFE CYCLE COST ANALYSIS

To manage the infrastructure efficiently, the cost implications of alternative actions have to be known (or estimated) and considered. These costs are used in the comparison of alternatives for project level decisions and also in ranking and optimization routines for network level decisions.

For a system of bridges, the costs that have been considered are direct and indirect costs that will be incurred by the agency and the public. Costs incurred by the public should be given as much weight as those incurred by the agency, even if they are less tangible and more difficult to estimate, because costs incurred by the public make up most of the total costs, and the ultimate mission of the agency should be to provide the best service to the public. Costs incurred by the public can be divided into user and nonuser costs. Usually only user costs are considered because it is unclear to what extent the alternative actions taken by the agency can be regarded as the sole cause of nonuser costs, such as pollution, and because of the possibility of double counting of costs and benefits as with economic development effects. Regression analysis is especially useful for estimating agency and user costs as functions of bridge element conditions, deficiencies, and traffic volume, as will become clear.

Agency Costs

Agency costs include the resources such as funds, worker and equipment time, and materials consumed in bridge related activities, such as routine maintenance, rehabilitation and replacement. To estimate the costs of these activities, a good cost accounting system is essential. The type of action performed on each bridge element, the costs incurred for the bridge element, and the condition of the bridge element before and after the activity, and other relevant data should be recorded. Data needs to predict bridge related costs are discussed in this *Circular* by Turner and Richardson (*1*).

Routine Maintenance Costs

The costs associated with the routine maintenance of bridge elements can be estimated directly or indirectly. Directly, these costs would be estimated as a function of the material type, condition, location, average daily traffic (ADT), highway classification, and other important factors for each bridge element. Indirectly, these costs can be estimated by first estimating the quantity of different routine maintenance activities performed on a type of element per year, as a function of element condition, material type, ADT, highway classification, environment and other factors. The unit cost of each type of maintenance activity is also estimated as a function of such factors as material type, highway classification, and other factors. Together, the quantity of routine maintenance activities per year and their unit costs give an estimate of the routine maintenance costs. With the necessary data, regression analysis can be used to estimate both the quantity of work to be done and unit costs for each type of work. An example can be found in the study by Purdue University for the Indiana Department of Transportation (*13*).

Element Rehabilitation Costs

The costs associated with the rehabilitation of bridge elements should be estimated for different types of elements and the different rehabilitation alternatives applicable for each element type. A good data base/cost accounting system is essential to provide accurate and up-to-date cost estimates, broken down to individual element rehabilitation level. Unit costs of the deck reconstruction and overlay alternative were estimated with regression analysis for the Indiana DOT with the following factors: region of the state, highway system, traffic volume, bridge length, deck area, and percent of area needing patching (*13*).

Element Replacement Costs

The principles involved in estimating element replacement cost are the same as those for element rehabilitation cost. The element replacement costs should be estimated separately to recognize element replacement as a separate alternative action and because the funding options for element replacement might be different from those for element rehabilitation. In a study by Purdue University for Indiana DOT, superstructure replacement cost was modeled for different superstructure types as a function of bridge length and deck width. Substructure replacement cost was modeled for different substructure types as a function of bridge length, deck width and vertical clearance. Approach construction cost was modeled as a function of the approach length and the amount of earthwork. Other costs and total bridge costs were modeled as a function of bridge length and deck width (*13*).

Bridge Replacement Costs

Bridge replacement cost estimation should be done by breaking the total project down in the different cost items, and then using historical contract costs for similar items on similar projects to estimate these cost items. For preliminary estimation, simplified methods can be used. Bridge replacement cost would depend on the length, width and height of the bridge, the number and length of the individual spans, the superstructure and substructure material and structural type, as well as the bridge location and the feature (e.g., road, rail or river) being crossed. Using the deck area to estimate replacement "base cost" is proposed in the paper by Chen and Johnston (*14*).

User Costs

User costs include all additional costs incurred by road users over those costs that would have been incurred if the bridge system had been in a specific predefined "ideal" state. User costs are therefore incurred even (and especially) if there is no bridge in place, and when a bridge suffers from deficiencies, such as insufficient load capacity. The development of user costs for bridge management systems is discussed by Johnston et al. (*4*), and only a few points are mentioned here.

Additional User Costs Due to Detours

User costs can be incurred because vehicles have to take detours because of insufficient vertical clearance or load capacity. These costs will consist of additional vehicle operating costs and the value of the time lost. The additional congestion and pavement damage caused in the rest of the transportation system also should be considered, if this effect is likely to be significant. To estimate these user costs for life cycle cost analysis, the following data analysis techniques can be used:

- Estimate the future traffic using a time series or regression analysis. For a simplified analysis the historic traffic growth rate along the same or a similar route is usually extrapolated over the analysis period.
- Load capacity can be predicted directly using techniques such as regression analysis or Markov Chains, or indirectly by using these techniques to predict the conditions of the applicable structural elements and then derive the load capacity from these element conditions.
- With the necessary data, elementary techniques from descriptive statistics can be used to estimate the distribution of different vehicle types on different routes, the distribution of vehicle weight and height for each vehicle type, the numbers of different types of vehicles detoured due to insufficient bridge load capacity or vertical clearance, the vehicle operating costs per distance for different types and weights of vehicles, and the additional vehicle operating costs and time costs due to bridge deficiencies.

Accident Costs

To estimate the costs due to bridge related accidents, the following have to be done:

- Estimate the expected rates of different types of accidents at each bridge as a function of its deficiencies. Accidents involving bridges are on average more serious than general vehicle accidents on the open highway (*14*). Therefore highway accident statistics should not be used to estimate rates of different severity levels of bridge related accidents. With sufficient data, regression analysis can be used to estimate rates of different accident types as a function of bridge deficiencies.
- Estimate the costs of the different types of accidents related to bridges. This is usually done by separately considering the direct and indirect accident costs. Direct costs include more "tangible" costs, such as medical, property damage and legal costs. Indirect costs include the value of the more intangible losses such as pain, loss of quality of life, and losses in future

production and income. Two approaches to determine accident costs are discussed in the paper by Chen and Johnston (*14*).

The rates of different accident types and their associated costs together give an estimate of the expected accident costs due to bridge deficiencies. Often the necessary data to estimate the costs of bridge related accidents as a function of bridge deficiencies will not be available. The effect of deficiencies on accidents also can be considered in a more qualitative way by constructing a "Bridge Safety Index" as described in a publication by Murthy and Sinha (*10*). In this study, bridge inspectors provided the subjective judgments. These subjective ratings were then regarded as elements of a fuzzy set and transformed to fuzzy numbers. Bridge characteristics, approach roadway and environmental conditions were the factors considered as influencing bridge safety.

Additional User Cost During Bridge Work

Bridge work, whether routine maintenance, rehabilitation or replacement, usually influences traffic flow both across the bridge and on surrounding roads. The congestion caused by different alternatives can differ in terms of severity, duration and frequency. Routine maintenance might cause less severe congestion for a shorter period than rehabilitation, but this congestion will occur more frequently. Bridge work therefore causes additional user cost due to increased congestion. These additional user costs are incurred by users of the bridge and by users of the surrounding road network that have to put up with the additional congestion during periods of bridge work. The additional use of alternative routes during bridge work also may cause accelerated deterioration of the roads and bridges along these routes.

Identification of Promising Alternatives

Many bridge maintenance, rehabilitation and replacement alternatives may be feasible for each situation. Although ideally all alternatives should be considered, for practical purposes it is desirable to develop a reduced list of more promising alternatives for each situation. The situation can, for example, be a combination of deficiencies, element material types, bridge structural types, climatic environment, and ADT. Each alternative is then analyzed with its activity profiles and cash flows for project level decisions, or with the promising alternatives of other bridge projects for network level decisions. An example of such an exercise is the study conducted for the Pennsylvania DOT to identify cost-effective bridge maintenance and rehabilitation alternatives (*15*). In another study for Pennsylvania DOT, it was found that even if the maintenance requirements are assessed on a broad basis, detailed needs have to be quantified for each bridge. A list of potential bridge maintenance activities was later developed (*15*).

The detail with which alternatives are formulated will depend on the level that the available data will permit and the level at which the analyst wants to make distinctions between different alternatives. Results specifying specific actions for each bridge can obviously not be expected if data of sufficient detail were not collected and the alternatives were not specified with the necessary level of detail. It also should be kept in mind that if the analysis does not include a sufficient level of detail, the results may be so crude that they are almost useless, and a manual, judgmental procedure might have achieved better results, even for network level analysis. In a study for Indiana DOT it was found that the level of distinction between bridge rehabilitation activities was too broad and an enlarged list was suggested (*13*).

Activity Profiles and Cash Flows

The next step in analyzing different alternatives is to construct the activity profile associated with each alternative. For this all the results of previous analyses are brought together. The current condition and ADT determines current agency and user costs, and which alternatives are currently feasible. The models developed to predict condition are used to predict the condition for different alternatives. These are then used with the models for agency and user costs to estimate the associated costs for each alternative activity profile, and thereby to derive each associated cash flow. The cash flow of each activity profile can then be analyzed with the techniques of interest accounting.

Commonly used criteria for selecting or ranking alternatives are Net Present Value, Equivalent Uniform Annual Cost, Incremental Benefit/Cost Ratio, and Incremental Internal Rate of Return. If the analysis is done correctly, these criteria should lead to the same preferences of alternatives relative to each other. Many reference works describe the application of these techniques, such as Grant, et. al. (17). Several issues have to be addressed when conducting these analyses. The first is the choice of a minimum acceptable rate of return. Theoretically, the chosen rate should be the rate of return that can be earned on projects or investments with a similar level of risk. The rate of return to be used is often suggested to be the yield rate on some type of long term government bond adjusted for inflation. The way in which inflation is to be considered is described in the literature, e.g., Grant, et. al. (*17*). Usually the service lives of alternatives will be different. One approach is to use the same cutoff date for all alternatives, after a long analysis period. Differences between alternatives after this cutoff date are then represented by different residual or salvage values. Another approach is to assume that each life cycle after bridge replacement is repeated into perpetuity. If this approach is followed, the ADT has to be stabilized at some value. Another issue to be addressed is exactly which costs should be considered. Agency and user costs, as influenced by the alternatives, have to be included. Nonuser costs, such as those associated with air and noise pollution, aesthetics and ecological disturbance, are difficult to relate to alternatives and to estimate. Most studies currently ignore these cost elements or take these effects into account in a more qualitative way. These factors will become more important in the future.

Impact Analysis

Even where programs for systematic data collection and analysis have been instituted, it may take many years before sufficient data have been collected to apply techniques such as regression analysis and Markov chains. A need therefore exists for simplified impact estimation to support decisions that have to be taken in the meantime. A common approach is to obtain the judgment of bridge experts regarding the impact of alternatives. Such an approach was followed by the Pennsylvania DOT to identify a list of cost-effective maintenance and rehabilitation alternatives with their impacts on costs and safety (*15*). The developers of Pontis suggested such an approach as an interim measure to obtain estimates of deterioration rates and condition impacts (*5,6*).

In a study conducted for the Indiana DOT by Purdue University the Delphi technique was used to obtain judgmental impact estimates by iteratively building a consensus among bridge experts. This technique was used to obtain estimates of the impact of routine maintenance only, deck patching, deck reconstruction and deck replacement, on the remaining service life of bridges (*8*).

PRIORITY SETTING AND OPTIMIZATION

Several approaches and techniques have been developed to assimilate data and analysis results to make better decisions. One approach is that of priority setting, usually done by ranking projects according to some criteria to obtain a priority order list of projects. Another approach is that of optimization, where the objective is maximized/minimized subject to constraints by choosing the best values of the decision variables.

Priority Setting

Many ranking methods have been developed to aid in priority setting. Most ranking methods develop a composite index or indices for each bridge or each project. Bridges or projects are then ranked according to the values of these indices. One such method is the sufficiency rating which is developed according to the FHWA's *Structure Inventory and Appraisal Guide* (*18*). This makes provision for the calculation of indices reflecting the structural adequacy and safety, the serviceability and functional obsolescence, the essentiality for public use and the overall sufficiency rating.

Bridges also can be ranked according to level-of-service criteria. Such a method that ranks bridges according to deficiency points, was proposed by Johnston and Zia for North Carolina DOT (*19*). The method takes load capacity, clear deck width, vertical overclearance and underclearance, remaining service life and the costs of alternatives into account.

There are many methods based on pairwise comparisons between bridges and alternatives. Concordance analysis is such a method that has been used to select transit improvement alternatives and in bridge evaluation (*8*). Another method was developed using linear programming to estimate the weights of multiple attributes in constructing a composite criterion (*8*). The analytic hierarchy process is a pairwise comparison method and will be briefly discussed. A disadvantage of all these pairwise comparison methods is that the number of pairwise comparisons become very large as the number of alternatives increases.

Assignment of Relative Weights

The analytic hierarchy process (AHP) constructs a hierarchy and uses pairwise comparisons at each level of the hierarchy. System goals, objectives, criteria and alternatives are related by the hierarchy. Relative weights are given to "activities" on the same level in the hierarchy for measuring their contribution to an "activity" on an adjacent higher level. For a bridge management system, the first level might be the goal to maximize system effectiveness. The second level might consist of objectives based on achievement of the goal to be measured, such as bridge condition, agency costs, user costs, safety and external impacts. The third level might then consist of the criteria, in terms of which each objective is measured. The criteria for user costs might consist of additional vehicle operating costs due to detours, value of time lost, additional congestion caused and accident costs. The fourth level might then consist of individual alternative projects.

The above hierarchical structuring is very general, and similar structures are used in many ranking methods. What makes the AHP method different is the way in which the relative weights are derived. The activities on each level are pairwise compared to produce relative weights. Then these relative weights are arranged in a reciprocal matrix for each higher level activity. If the pairwise comparisons are consistent, an eigenvector corresponding to the largest eigenvalue will give a set of relative weights for all the activities. Alternatives can then be ranked according to these weights. More information on the AHP can be obtained in Saaty (*20*).

Utility Functions

Many alternatives might have to be compared in bridge management. Making pairwise comparisons between all alternatives with respect to each criterion might therefore be an enormous task. In the bridge management system developed by Purdue University for Indiana DOT, this problem was resolved by developing utility functions for the bridge characteristics, such as remaining service life, that will be impacted by alternatives. To compare alternative projects, the characteristics of the bridges can be directly converted to utility points without having to make pairwise comparisons between all alternatives (*8*).

Optimization

The purpose of optimization is to find the optimal set of actions to be implemented at different times on a network of bridges subject to a variety of constraints.

Minimization of Life Cycle Costs

One approach is to do a life cycle cost analysis for each bridge or type of bridge in the system, for each promising alternative that can be implemented at each programming period. This reduces to continuing with routine maintenance until one of the rehabilitation or replacement alternatives is better than routine maintenance. A similar approach was followed by North Carolina State University in their study for North Carolina DOT (14), and by Wisconsin DOT (*21*). This approach does not find a "true global" optimum strategy, because it does not simultaneously take network-wide effects such as budget constraints into account, and at the point in time that an alternative is chosen, future choices are not yet determined. To choose the optimum alternative under these conditions, some simplifying assumptions about future alternatives usually have to be made.

Linear and Integer Linear Programming

One of the most versatile optimization techniques is linear programming (LP). In such a program, the values of decision variables are sought that will maximize/minimize a linear objective function, subject to linear equality/inequality constraints, such as budget constraints. The decision variables should be such that they can realistically be regarded as continuous variables. The Pontis MR&R models, including the deck maintenance models and the substructure-superstructure optimization models, were formulated so that they can be solved with linear programming. Decision variables for the different models include expected discounted cost, and the limiting probability that an element will be in a state and an action will be chosen (*5,6*). These are all continuous variables.

Often the decision variables are discrete, such as whether an alternative will be implemented ($x=1$) or not ($x=0$), resulting in an integer linear program (ILP). One very simple version is as follows:

$$\min \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{a=1}^{A} c_{ait}\, x_{ait}$$

subject to

$$\sum_{i=1}^{I} \sum_{a=1}^{A} b_{ait}\, x_{ait} \le B_t \qquad \forall t = 1,\ldots,T$$

$$\sum_{a=1}^{A} x_{ait} \le 1 \qquad \forall i = 1,\ldots I,\ t = 1,\ldots,T$$

$$\sum_{u=t}^{t+\tau} x_{aiu} \le 1 \qquad \forall a = 1,\ldots,A,\ i = 1,\ldots,I,\ t$$

$$x_{ait} = 0 \text{ or } 1 \qquad \forall a,i,t$$

Each alternative a for each bridge i for each programming period t is associated with a decision variable x_{ait}, associated total (agency and user) costs c_{ait} and associated budget requirement b_{ait}. Each decision variable x_{ait} indicates whether the alternative is chosen ($x_{ait} = 1$) or not ($x_{ait} = 0$). The objective function minimizes the total costs over a finite time horizon, T.

The first constraint ensures that the budget for each programming period t is not exceeded. Budget constraints also can be split between various sources and accounts. The second constraint ensures that at most one alternative is chosen for each bridge in each programming period. The third constraint ensures that the same alternative is not implemented more than once for a specific bridge during a time window. Similar constraints can be formulated for mutually exclusive as well as for interdependent projects. An ILP model was proposed for the improvement model of Pontis (*5,6*), as well as for the Indiana BMS (*2*).

Advantages of LP and ILP are:

- These techniques are very versatile, easy to understand, and can be used to formulate and solve a wide variety of optimization problems. Formulations can be changed to adjust to changing needs and circumstances.
- Software for linear and integer linear programming is available.
- Linear programs with hundreds of thousands of decision variables have been solved.

Disadvantages of LP and ILP are:

- The size of *integer* linear programs that are solvable in reasonable time is much more restricted than that for linear programs.
- Objective functions and constraints are restricted to linear functions of the decision variables. Some nonlinear functions can be approximated by piecewise linear functions, but this complicates the exercise. Nonlinear objective functions and constraints also can be handled with the techniques of nonlinear programming. This is computationally much more demanding.

Dynamic Programming

An optimization approach with more desirable computational properties is dynamic programming. It is based on the Principle of Optimality which in this context means that optimal alternatives/policies over time consist of optimal subalternatives/subpolicies over shorter periods. This is in general true for bridge management. Thus, optimal policies can be constructed by recursively finding optimal subpolicies for successive programming periods. One method of applying dynamic programming is to do the analysis over a finite, but long, time horizon. At each stage a bridge element can be in several different states. A terminal value/cost is assigned to each state at the end of the analysis period. A cost is also associated with being in each state at each stage and with the implementation of each alternative in each state.

The optimal alternative can be calculated recursively for each state at each stage. The transition probabilities can be given as the transition matrix of a Markov chain, as long as the underlying assumptions of a Markov chain are satisfied. Such an approach has been suggested for several pavement and bridge management systems (*5,6,2*). If optimal alternatives are consistently implemented, the state of the system will move towards an optimal steady state. A useful analysis is therefore to determine the optimal steady state and associated alternatives. Because the system will not be in this optimal steady state, an associated problem is the optimal way of moving towards the optimal steady state. Both the optimal steady state problem and the optimal transition stage problem were formulated as linear programs for Pontis (*5,6*). An optimization model developed by Purdue University for Indiana DOT combines dynamic programming and integer linear programming. Different budgets for each stage are incorporated in the dynamic program's state space. At each stage the optimal set of projects for each budget is selected with integer linear programming. The objective is to maximize a measure of system effectiveness that takes ADT, bridge element conditions, traffic safety and community impact into account (*2*).

Network and Heuristic Methods

Because realistic optimization models are computationally demanding to solve, heuristic procedures might hold promise. Limited study has been done in this field. An example is an investment staging model for bridge replacement proposed by Garcia-Diaz and Liebman (*22,23*). This model specifically addresses the replacement and scheduling of rural bridges. It explicitly takes the user cost into account especially the cost of alternative routes due to bridge load capacity deficiency. It minimizes road user cost subject to agency budget constraints. The problem is simplified by a form of decomposition by separately scheduling bridge replacement projects over different subhorizons. The subhorizons are ordered in a priority sequence—an application of lexicographic optimization (*22,23*). Heuristic methods might be more effective due to the complexity of bridge management.

CONCLUSION

The nature and sophistication of an agency's bridge management system, and data analysis in particular, will be determined by the system of bridges for which the agency is responsible, and the available resources. Some larger cities with many bridges with a heavy traffic load might have bridge management system needs similar to those of state highway agencies, whereas some small cities might have only a few bridges to take care of, and very few resources. For such small cities bridge management would be mostly at the project level. Network level analysis would add little additional value. Some counties might have many bridges, but few resources to take care of those bridges. The bridge management needs of such counties would differ from those of states and cities.

Bridge management is a continuous process. Changes are continuously occurring—bridge elements deteriorate are rehabilitated or replaced, traffic levels change, costs change and available resources change. Bridge management activities should therefore be conducted on a continuing basis - data collected, database updated, reports generated, models developed, conditions and impacts predicted, alternatives evaluated and optimal strategies selected. Due to this dynamic nature of the bridge management process, systems should be frequently improved—new data analysis techniques developed, better models estimated, better optimization techniques developed and better decision making methods implemented.

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