Network-Level Bridge Management Systems for National Road Administrations

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ABSTRACT

National governments must provide guidance on general needs of the bridge stock at an aggregate level. National agencies are beginning to invest in decision support systems assisting in this planning process. The paper summarizes two current efforts in this area undertaken in the U.S. and Sweden in the form of design and implementation of bridge management systems. Both systems feature interactive real-time "What-If" analysis based on optimization and simulation of the process of budget allocation for the national stock of bridges over a long-term period. Budget is allocated to satisfy the needs for maintenance, repair and rehabilitation as well as to correct the functional deficiencies of the bridges.

The purpose of the systems is to simulate the influence of the policy factors on the network performance over a substantial time horizon for multiple measures of effectiveness. Bridge population is broken down into strata groups following the stratification schemes accepted by the two agencies. The results of the simulation are obtained in a compact parametric form suitable for the "What-If" analysis. Proposed projects are grouped and prioritized by their benefit/cost ratios using the agency-specific evaluation models.

"What-If" analysis is performed in real time, making it possible to see immediately the results of the given policy. Analysis is based on interactive graphical interface that allows the user to set targets, vary budget levels and monitor network performance in both graphical and tabular form.

OVERVIEW

For a national government, the task of bridge management is substantially different from the similar task performed by regional transportation agencies. Both types of agencies share a common ultimate goal, but the two types of agencies tend to have very different processes with different methods and different constraints.

On the regional level, the task of bridge management can be briefly summarized as working out of an optimal resource allocation plan. The essential features of such a plan are a budget that has been constrained by outside factors as part of input, and bridge-by-bridge project level recommendations as its output.

The task of the national government, on the other hand, is often to provide guidance to legislative bodies. This guidance is commonly delivered as a report of general aggregate needs of the national bridge stock. The national reports of bridge needs do not deal with individual bridges. With respect to budgeting, the task of national government is to determine the minimum level of funding needed to bring the stock of bridges to the desired condition level.

Therefore, the national planning body often has to solve a problem that is the *exact opposite* to that of the regional agency. Instead of allocation of a pre-defined limited budget, the national planning body has to help set the budget that the regional agencies will use.

It is not possible to characterize the aggregate condition of the national bridge stock using a single indicator. Condition reports and forecasts inevitably have to include numerous characteristics, all of them having important descriptive features. Some of these characteristics are expressed in monetary terms (e.g., total maintenance needs), others in physical terms (e.g., number of functionally obsolete bridges). Some of the indicators describe different kinds of bridge needs while others deal with user benefits. The variety of characteristics combined with their multi-year tracking make the task of the national long-term bridge management planning a highly multi-dimensional problem. Finally, the various important decision-makers, who are generally not bridge specialists, can be expected to place different importance on different characteristics.

A major part of the planning exercise is evaluation of the impacts that different changes in various planning policies may have on the aggregate characteristics of the bridge stock. These impacts are studied in the form of *scenarios* that are evaluated and compared to each other thus making a base for the reports presented by the national government to the legislative body. Using this type of process, it is important for the national agency to be able to produce, evaluate and compare a desirably large number of scenarios in order to craft a long-term plan. It is also important for a scenario to present the variety of its information items in a concise form.

Realizing the complexity of a scenario-based long-term planning process, national agencies are beginning to invest in decision support systems to facilitate this process. This paper describes two efforts in this direction that are being currently undertaken in the U.S. and Sweden. The National Bridge Investment Analysis System (NBIAS) has been recently developed for the U.S. Federal Highway Administration (FHWA). A similar system, PLANOPT, is being currently developed for the Swedish National Road Administration (SNRA) for delivery during the year 2000.

The planning processes and methods adopted by the two national administrations are considerably different. The standards and level of detail of the bridge inventory data maintained at FHWA and SNRA are also different. Therefore, in their analytical part, NBIAS and PLANOPT are two completely different systems. When it comes to using the analytical results, both systems share the same common concept in scenario analysis, and therefore will be reviewed together.

CONCEPT

The concept that underlies the approach to the design of the systems for national long-term bridge management planning can be summarized by its following essential features:

- aggregation and stratification of the bridge data;
- reporting on multiple condition indicators (measure of effectiveness);

- encapsulation of the planning assumptions and output characteristics in the form of a scenario;
- multi-year program simulation;
- parameterization for a number of budget levels; and
- interactive "What-if" analysis of the scenario using a variety of graphical devices.

From an implementation perspective, there are two important issues: The first issue is to establish an independence from a particular planning method adopted by the national agency. This independence allows certain flexibility in postulation of the planning assumptions, criteria and quantitative characteristics and thereby makes it possible for the national agency to "program" the planning system.

Another important issue is separation of the analytical part of the planning process from the 'What-If' analysis. The analytical part of the planning process is based on the simulation principles. Given the size of a national bridge inventory, multiple years of the planning horizon and complexity of the planning methods, simulation may take several hours and even days. At the same time, it is very desirable for the system to be able to provide an immediate response to a change in the planning assumptions and deliver this information in a concise and easy to understand form. This dilemma is solved through parametric simulation being run as batch-like process and "What-If" analysis implemented as an interactive post-processor that operates on the tabulated data accumulated through simulation.

AGGREGATION AND STRATIFICATION OF THE BRIDGE DATA

NBIAS

Aggregation of the bridge data is a prerequisite for its processing in the NBIAS system. The U.S. national bridge inventory contains about 525,000 bridges of the minimum required size (not including culverts, which are not considered). Therefore, it would not be feasible from a performance perspective to address each bridge individually in a system that does not have bridge-level analysis among its objectives.

Instead of managing individual bridges, NBIAS groups them in a smaller number of 'cells', where each cell represents a group of bridges that have common modeling characteristics. In this context, these common characteristics are called *strata* and the process of grouping bridges—*stratification.* For modeling purposes, NBIAS considers the following stratification dimensions for a bridge:

- functional classes;
- relationship to the National Highway System (NHS, i.e., on NHS or off NHS);
- average daily traffic (ADT) class; and
- climate zone.

The numbers of categories in each of the dimensions are: 13 functional classes, two NHS categories, five ADT classes and four climate zones. Thereby, for the modeling purposes, NBIAS has to operate on ($13 \times 2 \times 5 \times 4 = 520$) cells. The underlying assumption is that for the purposes which NBIAS' users will need to consider, within each cell all bridges have the same modeling characteristics.

Aggregation of the bridges occurs in NBIAS through processing of a standard National Bridge Inventory (NBI) data set. When the NBI file is processed, each bridge is analyzed for its functional and structural needs. Once the needs and other characteristics (e.g., deck area) of a bridge are estimated they contribute to one of the 520 cells.

NBIAS distinguishes between the modeling and reporting stratification schemes. The modeling stratification scheme described above needs to be as detailed as necessary to capture differences in modeling assumptions. For the reporting purposes, NBIAS uses a subset of the modeling stratification scheme that includes only the functional class and the NHS category. Thus, NBIAS reports the results of its analysis for 26 individual strata of the bridges' population.

PLANOPT

The issue of aggregation in the PLANOPT system is not imposed by the size of the inventory. The national bridge stock of Sweden contains roughly 12,000 bridges, so it is technically feasible to keep track of all of them individually. However, for the modeling as well as for the reporting purposes, the national bridge population of PLANOPT still needs to be stratified. Since the modeling principals adopted by the SNRA require a bit more detail than those of the FHWA, the stratification scheme of PLANOPT is more complicated. For the purposes of modeling, the following stratification dimensions are adopted in PLANOPT:

- road category (National, Regional, County or Other);
- county (administrative ownership);
- design standard;
- construction type;
- material type;
- climate zone;
- ADT class.

In contrast to NBIAS, where the numbers of categories in each dimension are fixed, PLANOPT does not impose any specific limit for them. The numbers of design standards, construction types, climate zones etc. can all be variable and come as a part of the system's input. It was possible to allow this kind of flexibility because the number of bridges operated by the SNRA is relatively small, and internally all information in the system is still maintained on a bridge level.

The SNRA had chosen for output to build the reports by road category and county.

MEASURES OF EFFECTIVENESS

On the national level, the bridge network performance is monitored in the systems through a broad range of indicators, commonly called measures of effectiveness. Collectively, these indicators allow describing the condition of a bridge stock in many different aspects. NBIAS and PLANOPT employ different sets but overlapping of measures of effectiveness, and all measures used can be described in common terms regardless of system.

Most of the measures are used to indicate different types of needs. For every planning period, three measures of effectiveness are associated with every kind of a need: need at the beginning of the year, work done and backlog at the end of the period. Some of these measures have only monetary expression, e.g., "Maintenance needs backlog"; others exist in both monetary and physical versions, e.g., "Bridge replacement needs—$M" and "Bridge replacement needs—number of bridges."

A "need," however, can be decomposed into a number of parts. For example, improvement needs may be broken down into different functional categories, such as widening or raising.

Another group of measures of effectiveness is related to the user benefits. As with to the needs, each type of benefit has three associated measures of effectiveness: potential benefit at the beginning of the year, benefit obtained through the simulated work and backlog in user benefit at the end of the year. The benefit-related measures of effectiveness are expressed in monetary terms only.

The last group of indicators is made up of the measures describing the simulation process itself. This group contains the cutoff and cost-weighted averages of benefit/cost ratios calculated for different types and groupings of the simulated projects.

In total, NBIAS operates with more than 60 different measures of effectiveness. PLANOPT, which delivers its output in a less detailed form, operates with 36 measures.

SCENARIO

The concepts used to simulate needs differ between NBIAS and PLANOPT. NBIAS is capable of simulating maintenance, improvement and replacement needs using a combination of optimization models and user-specified policies, whereas PLANOPT is a purely policy-driven system with deterministic models and policies. Nevertheless, both systems allow users to maintain more than one set of the policies, cost and transition probabilities matrices and other modeling inputs. In this fashion, users can understand how underlying policy changes can affect planning decisions.

Variation of the modeling assumptions and their association with a particular bridge data is implemented in NBIAS and PLANOPT through the concept of a scenario. The scenario is also the mechanism through which the analytical engines of the systems communicate with their "What-if" analysis modules.

From the user's point of view, a scenario is an informational object that ties together the bridge stock data, modeling assumptions, and—after the scenario has been 'run'—the simulation results.

The first two components, bridge data and modeling assumptions, have a completely different form between the two systems. The concept of the scenario, however, remains the same, as does the format of the simulation results, which remains common between NBIAS and PLANOPT.

Once the modeling specifications and the set of the input bridge data are specified, the scenario can be '*run.*' *Running* of the scenario is a process of simulation of allocation of a limited annual budget to the bridge population. Simulation of the needs is done according to the modeling assumptions specified in the scenario. The sets of the assumption parameters as well as the policy rules in NBIAS and PLANOPT are different. Benefits associated with the needs are calculated according to the proprietary methods established by the models used at the two national agencies. A need with its type, cost and associated benefit becomes a *synthetic project* within a scenario. It is important to realize that due to the aggregated nature of the national level planning, one project does not necessarily represent a bridge; in NBIAS it may also represent a stratum of bridges.

Limited annual budget is allocated to the projects in order of their benefit/cost ratio. Projects that are funded have their needs taken away and their benefits added to the totals. As the synthetic projects are being implemented (done) or rejected (delayed) the condition of the bridge stock improves or deteriorates according to the rules established in the modeling assumptions.

MAINTENANCE MODELING

In both systems, evaluation of maintenance needs is based on the condition of the object of planning and the adopted maintenance policy. In general, the cost of maintenance is proportional to the size of the planning object, and the benefit is based on the concept of saving. Beyond these common principals, NBIAS and PLANOPT employ modeling methods that are quite dissimilar. The major differences between the two systems are as follows:

- The object of planning in NBIAS is an abstract entity of an aggregated condition unit while PLANOPT operates with individual bridges.
- In NBIAS, bridge network is looked upon as a collection of core elements (such as decks, superstructures, substructures, girders, etc.). The condition of the network is projected through the condition of the elements. PLANOPT does not use element level decomposition; instead, it operates with the integral condition characteristics of the Lack of Capital Value (LCV). LCV is a form of health index that estimates the funds necessary to return the bridge back to a "perfect" structural condition.
- NBIAS and PLANOPT use different condition language. In NBIAS, bridge elements deteriorate by going through a sequence of discrete condition states, whereas in PLANOPT, the primary condition indicator, LCV is a continuous function of the apparent age of a bridge.
- The dynamics of deterioration is introduced in NBIAS through the concept of Markovian chain, in which objects are making transitions between condition states. Each transition between a pair of states is characterized by its probability. In contrast to NBIAS, PLANOPT relies on a deterministic model, within which condition (expressed by LCV) is represented by analytical function of time.
- Like deterioration, upgrading of the condition is also modeled differently in the two systems. In NBIAS, the impact of a remedial action is expressed as a transition from the original state to one or more target condition states, where each of the transitions has its own. In PLANOPT, remedial actions are characterized by a fixed amount (or percentage) of LCV by which they reduce the current condition indicator.

- The maintenance recommendations upon which operates the simulation process have different origins in two systems. In NBIAS these recommendations come as a solution of a linear programming model that seeks an optimal maintenance policy for the given condition unit. The maintenance policy of PLANOPT is set entirely by the expert.

The following sections describe maintenance modeling issues for the systems individually.

MAINTENANCE MODELING IN NBIAS

NBIAS considers the bridge stock to be a collection of core elements. Depending on its type, each element may have from three to five condition states. Depending on the condition in which it operates, every element may find itself in one of the four environments ranging from Benign to Poor. These structural elements, quantified by their amounts (e.g., square meters of deck, number of girders, meters of railing) and characterized by the environment and quantitative distribution across the set of condition states, constitute *condition units*. In NBIAS, condition units are the primary objects of maintenance, and maintenance needs are evaluated for these units.

The optimal maintenance policy in NBIAS is built individually for each condition unit. In order to obtain this policy, a linear optimization model is solved for every element/ environment combination. This model seeks to minimize the long-term cost of maintenance for a dynamic system. The dynamic system formally presented as a set of constraint equations describes a condition unit in the process of its deterioration and maintenance along the infinite time horizon. This process is quantified by the transition probabilities and unit costs of the maintenance actions applicable in different condition states.

The numeric solution of the linear problem obtained for the dynamic system is translated by NBIAS into the terms of maintenance policy recommendations. In these terms, the optimal solution is delivered for each condition state in the form of a prescribed action and a unit benefit associated with this action. The set of model recommendations obtained for all condition units constitute the optimal Maintenance, Repair and Rehabilitation (MR&R) policy of NBIAS.

The first problem that NBIAS has to solve in order to be able to apply its optimal MR&R policy to the bridge stock is that the NBI data set does not carry the information about bridges' structural composition. NBI records do not contain any information about particular elements, their quantities and conditions. This problem has been solved in NBIAS through the introduction of the *Synthesis-Quantity-Condition* (SQC) models of structural elements.

SQC models allow estimation of the probability of presence of a certain element on a given bridge, its expected quantity, and the distribution of this quantity across the condition states. This information is obtained by applying the coefficients of the SQC models to the quantitative characteristics of a particular bridge that can be extracted from the NBI records, such as the size, design, material, rating codes etc.

The coefficients of the SQC are obtained through statistical regression analysis. Element quantities that can be evaluated through SQC coefficients have purely probabilistic meaning for individual bridges. Nevertheless, when these quantities are aggregated for the national bridge network they produce a reliable representative picture of the structural composition and condition of the bridge stock. As long as NBIAS is not concerned with particular bridges and is not supposed to generate bridge-specific project recommendations, SQC modeling makes a reasonable approach to synthesizing of the network element-level data. Initially, SQC models have been built using a sample of roughly 15,000 bridges for which both detailed element data as well as NBI data were available. These models are expected to continue to be refined as more element-level bridge data becomes available.

In order to apply the recommendations of the optimal MR&R model, NBIAS synthesizes condition data for the elements. Synthesized data is stored in the aggregated form of condition unit cells. Each aggregated cell represents one element, one Condition State, and one of the 520 bridge strata. The process of deterioration and upgrading is simulated in NBIAS through transition of the element quantities between the cells.

In the course of the simulation, recommendations of the optimal MR&R policy are applied to the condition unit cells. If the MR&R recommendation for the given cell is other than a *do nothing* action than the entire cell becomes an object of planning. The projected cost and benefit are calculated for the case when the recommended action is applied to the entire population of the cell. A synthetic MR&R project for the cell, which has been constructed thereby, enters the competition for the annual budget, a competition which is based on the benefit/cost ratios of the projects.

Depending on the availability of funds, a synthetic project may be funded fully, partially or not at all. If the project is fully funded then the upgrading transition probabilities of the recommended action are applied to the cell's population, which becomes distributed among the other cells of the same element/strata cross-section.

If the project cannot be funded then the content of the cell is distributed according to the transition probabilities of deterioration. Appropriate interpolations are done for the case when a project can be funded partially. Deterioration probabilities are unconditionally applied to the cells whose recommended actions are *do nothing*. Thus, after all synthetic projects of the cells have been processed NBIAS obtains the simulated condition of the bridge network for next year.

MAINTENANCE MODELING IN PLANOPT

PLANOPT does not aggregate bridge condition data and considers each of the twelve thousand bridges of the road network of Sweden individually. According to the methodology adopted at the SNRA, the primary indicator of the bridge condition is Lack of Capital Value (LCV).

LCV is the difference between the expected and actual economic condition of a bridge. LCV is expressed by the cost of the theoretical remedying measures that it is necessary to undertake for restoring the bridge to its required economic condition.

The bridge management methodology of the SNRA assumes that LCV consists of two components. The first component, LCV-b, is related to the condition of the structural elements that have impact on the bearing capacity of a bridge. The monetary expression for this component is theoretical cost of those remedying actions only that improve the bearing capacity of the bridge and bring it to the expected level.

The second component, LCV-d, is related to the durability of the bridge. Its monetary expression embraces the theoretical cost of the remedying actions that improve only the durability characteristics of the bridge without affecting its bearing capacity.

The monetary expression for LCV and its -b and -d components can be transformed into a relative form by dividing them by the theoretical renewal cost of the bridge. In its relative form, LCV is normally expressed in promille (1/1000th) fractions of the bridge renewal cost. In the PLANOPTs paradigm, LCV is used in its relative form.

PLANOPT simulates the deterioration process using deterministic functions of LCV over time. Within the operable range of values, LCV and its -b and -d components are approximated by the exponential expression:

$$LCV = a_0 + a_1 e^{rt}$$

Where t is the apparent age of the bridge in years, i.e., time since the bridge had been either constructed or rehabilitated to the zero-LCV condition.

Parameters, a_0, a_1 and r are estimated using regression analysis and may vary by strata.

The maintenance policy of the SNRA is set using expert elicitation. Decisions about doing remedying actions are based on the bridge condition expressed in the form of LCV components. These policies may vary across bridge strata, but generally, they are all proposed as combinations of the following generalized actions:

- Do nothing
- Minor maintenance
- Maintenance
- Major maintenance
- Replacement

Within each category (except the *Do nothing*), detailed actions can be specified.

The maintenance policy of PLANOPT is set up in the form of a matrix. For every bridge stratum, the maintenance policy matrix will contain ranges of values for LCV-b and LCV-d with actions recommended for the given range.

The agency cost of a maintenance action is considered to be a function of the bridge's condition and size. In theory, the monetary expression of LCV is supposed to be equal to the cost of the maintenance work that needs to be applied to the bridge in the given condition. In practice, however, it is not possible to use the monetary value of LCV as a proxy for the cost. The cost of maintenance is calculated from the base level of the LCV to which PLANOPT applies a swell factor, which must be specified as a part of the SNRA's maintenance policy.

Another component of the cost of a maintenance project is immediate user cost incurred because of the bridge posting and traffic congestion during the maintenance project. This cost depends on the following factors:

- Action type;
- Road category;
- Horizontal clearance;

- Bridge size;
- Average daily traffic on the bridge.

The action type and the bridge size are the proxies for the duration of the maintenance project. Road category and horizontal clearance represent the impact of the road works for the user: necessity of posting, severity of congestion etc.

It is assumed that in the absence of maintenance, when the bearing capacity of the bridge falls below a certain level, some fraction of the traffic has to bypass the bridge. PLANOPT accounts for this fact through using annual user cost incurred through the lack of maintenance.

As a part of the policy data, the SNRA provides unit annual user costs for cars and trucks. Using these unit costs, PLANOPT calculates the annual amounts of user costs accrued through the lack of maintenance on every given bridge. It is assumed that the unit values for this cost vary by bridge strata and apply only when LCV-b of the bridge falls below the threshold level established by the maintenance policy.

The SNRA methodology requires that benefits of the maintenance project accrue through annual savings in the agency and user costs. Savings in the agency cost are obtained through not having to do a more expensive action next year. Saving in the user cost is obtained as the difference in the immediate user cost between the current year and the year after plus the one-year amount of the user cost incurred through lack of maintenance. The total amount of benefit is calculated as a sum of the agency and user saving components with appropriate adjustments for the discounting and tax factors.

Once the maintenance needs of individual bridges are determined and their costs and benefits are calculated, PLANOPT generates maintenance projects and throws them into competition for the limited funds. As the projects compete for funds on the base of their benefit/cost ratio, any given project can be either funded or rejected. Since the project represents in this case a particular bridge, partial funding of a project cannot be considered.

If the maintenance project is funded its upgrading impact is simulated for the bridge through the reduction of the LCV by the amount (or by the fraction) specified for the given type of the action in the maintenance policy. If the project cannot be funded or no maintenance action is required, the apparent age of the bridge is increased by one year, and the appropriate values for its LCV components are evaluated. Once all projects are processed, PLANOPT obtains the next year's condition for all bridges.

FUNCTIONAL IMPROVEMENT MODELING IN NBIAS

In contrast to the MR&R activities, NBIAS models functional improvements on a bridge by bridge basis. NBIAS operates with improvement models for the following three types of functional needs: raising, strengthening and widening. These models exist in NBIAS in the form of logical rules parameterized with a set of numerical coefficients. Policy and cost parameters for the improvement models are stored in the form of Standard and Cost matrices where they can vary by bridge strata (functional class, ADT class, etc.).

As a part of the bridge compilation process, during which the element condition data is synthesized and aggregated, NBIAS applies the improvement models, which results in generation of synthetic improvement projects. Each synthetic improvement project generated by NBIAS carries the following characteristics:

- type of the functional need that it addresses (raising, strengthening or widening);
- cost of the project;
- user benefit of the project.

Although synthetic improvement projects are generated for individual bridges, no bridge specific information propagates to the project as it is not a goal of NBIAS to provide bridge specific recommendations.

If the functional need is identified on a bridge for which improvement is technically infeasible or disadvantageous because of the benefit/cost considerations, NBIAS generates for the bridge a replacement project. The cost of the replacement project is calculated based on the unit renewal cost per sq. meter of deck for the bridges of the given category. The benefit of replacement is considered to be equal to the benefit of satisfying the underlying functional need.

Improvement and replacement projects (that are implicitly bridge specific) come into the benefit/cost competition for funding with the MR&R projects (that are associated with condition unit cells). Once an improvement or a replacement project is selected (funded), it is removed from the list. Otherwise, it remains in the list until the simulation will be run for the next year.

FUNCTIONAL IMPROVEMENTS IN PLANOPT

PLANOPT does not have a formal mechanism for the evaluation of the functional needs. Recommendations for the improvement projects are submitted into the system as part of the bridge record. Estimates for the agency and user costs of the improvement projects as well as their expected user benefits are provided by the expert. PLANOPT combines improvement recommendations with the synthetic maintenance projects applying heuristic combining rules in situations when improvement and maintenance are scheduled on the same bridge.

Improvement and maintenance projects compete for the limited funds according to their benefit/cost ratios. Once an improvement project has been selected, it is removed from the list. Otherwise, PLANOPT carries it over to the next year.

SCENARIO SIMULATION AND PARAMETERIZATION

Although the methods employed by the two systems for the evaluation and quantification of the maintenance and functional improvement needs are different, the results of their applying are similar. In both cases a list of synthetic projects quantified by their costs and benefits is generated and sorted by the benefit/cost ratio. Simulation of the project selection is done by applying a limited budget to the prioritized project list. The effects of upgrading, improvement or further deterioration are simulated by applying the rules and models specific to the system. One-year simulation cycle results in the recording of quantitative indicators (measures of effectiveness) across a range of bridge strata. Measures of effectiveness and bridge strata are system specific.

Based on the next year's condition both systems generate a new list of projects, thus repeating the simulation cycle for all years of the planning horizon. Simulation is done for 30 years in NBIAS and for 20 years in PLANOPT. The sequence of one-year simulations performed for all years of analysis is called a *multi-year simulation cycle.*

PLANOPT and NBIAS parameterize the results of multi-year simulation by applying different levels of annual budget. As a part of the scenario specification, systems obtain the values of the maximum annual budget, *MaxBudget*, and the number of parametric steps, *N*. With this input, the systems perform *N*+1 parametric steps, going on each step through a multi-year simulation cycle. The annual budget distributed by the systems on each step is:

$$\text{AnnualBudget}[J] = \text{MaxBudget} * J / N$$

Where *J*, index of the parametric step, runs through the values from 0 to *N*.

Combined results of the parametric simulation make a four-dimensional data aggregate whose dimensions represent measures of effectiveness, strata, years of analysis and levels of annual budget. This data aggregate becomes the operational domain for the "What-If" analysis.

WHAT-IF ANALYSIS

Once having obtained the results of parametric simulation, the user of the bridge management system will want to obtain different information from these results. For example, the user may want to compare several effectiveness measures between themselves. Alternatively, he or she may want to see how the measures of effectiveness change with the variation of the annual budget, or to figure out how much funds must be spent annually for reaching a certain goal. In the context of the "What-If" analysis, these subsets of the scenario results are called *cross-sections.*

The number of possible cross-sections that can be made out of all possible permutations of the parameters in the four dimensional divisions can be quite high. On the other hand, the aggregate data object representing a single cross-section can be a two or three-dimensional array in itself. The task of representation of the cross-sections in the form suitable for visual evaluation is the main objective of the "What-If" analysis. This objective is achieved through the realization of the following concepts:

- "What-If" Analysis provides information in tabular and graphical forms.
- The number of templates for the tabular and graphical outputs is limited, but the user is able to configure them for a desired combination of output characteristics.
- The user can vary the budget inputs using graphical objects and obtain system response instantaneously.

The "What-If" module generates tabular output as *reports* and graphical output as *views*. There are six types of views and four report forms, which are shareable between PLANOPT and NBIAS.

The systems provide a variety of means, using which the user can change configuration of the views and make them respond to a particular combination of the input parameters. Some of the views have interactive objects (slider bars, buttons), using which the user can obtain the system's response to variations in his or her input in animation-like fashion. Configurable options are also available for the reports.

The following two screenshots illustrate interactive capabilities of the "What-If" module. The first screenshot contains a Budget Targeting view of the PLANOPT and NBIAS system. Using this view, the user can select a measure of effectiveness, a combination of strata categories and the number of years. By dragging the slider along the right hand vertical axis of the graph chart, he or she can set the target to be achieved at the end of the selected year. The system responds to this input by finding the minimum annual budget that would bring the inventory to the desired level of performance and then draws a corresponding curve.

The second illustration contains an example of a Cross-Criteria view. This view consists of six vertical panes. The user can set the characteristics of each pane individually by assigning it a measure of effectiveness and a strata combination. By dragging the horizontal sliders that represent year of the analysis and the annual budget, the user can monitor the system's response for up to six different indicators and bridge categories.

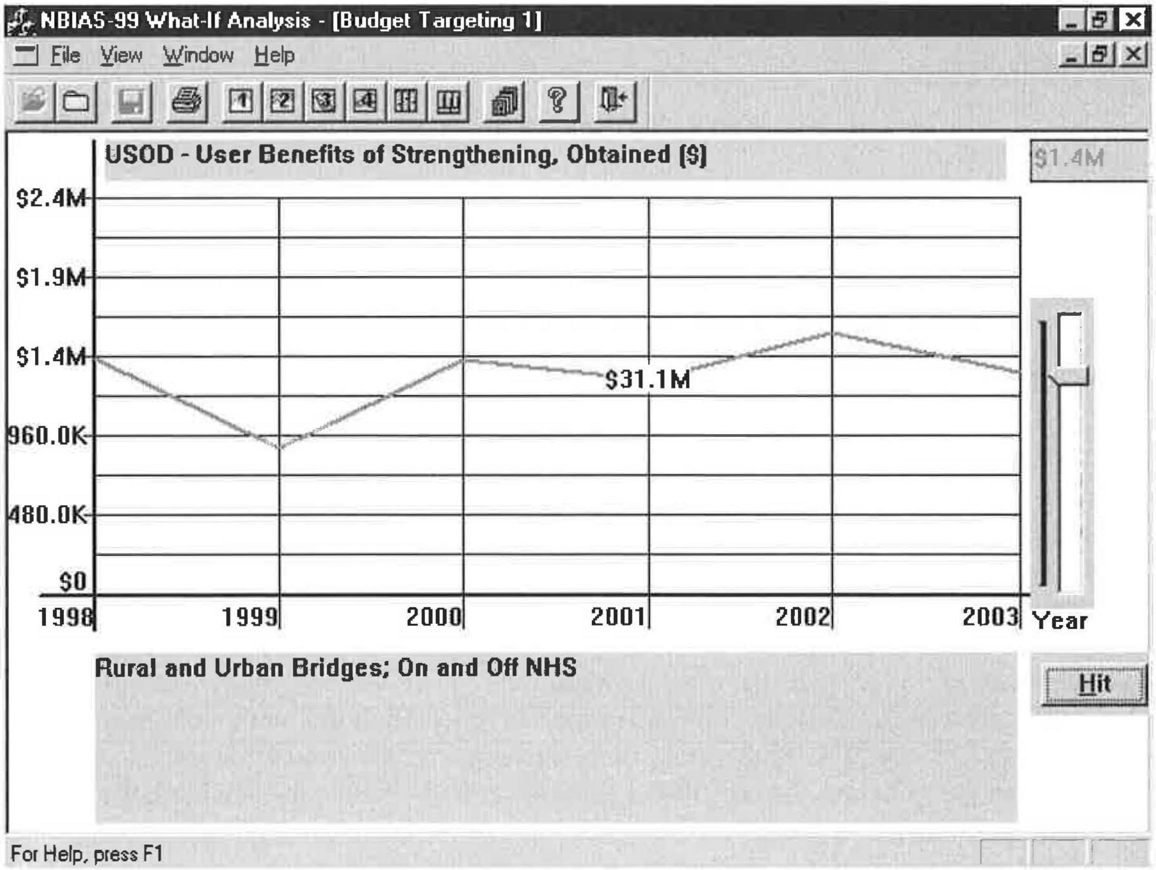
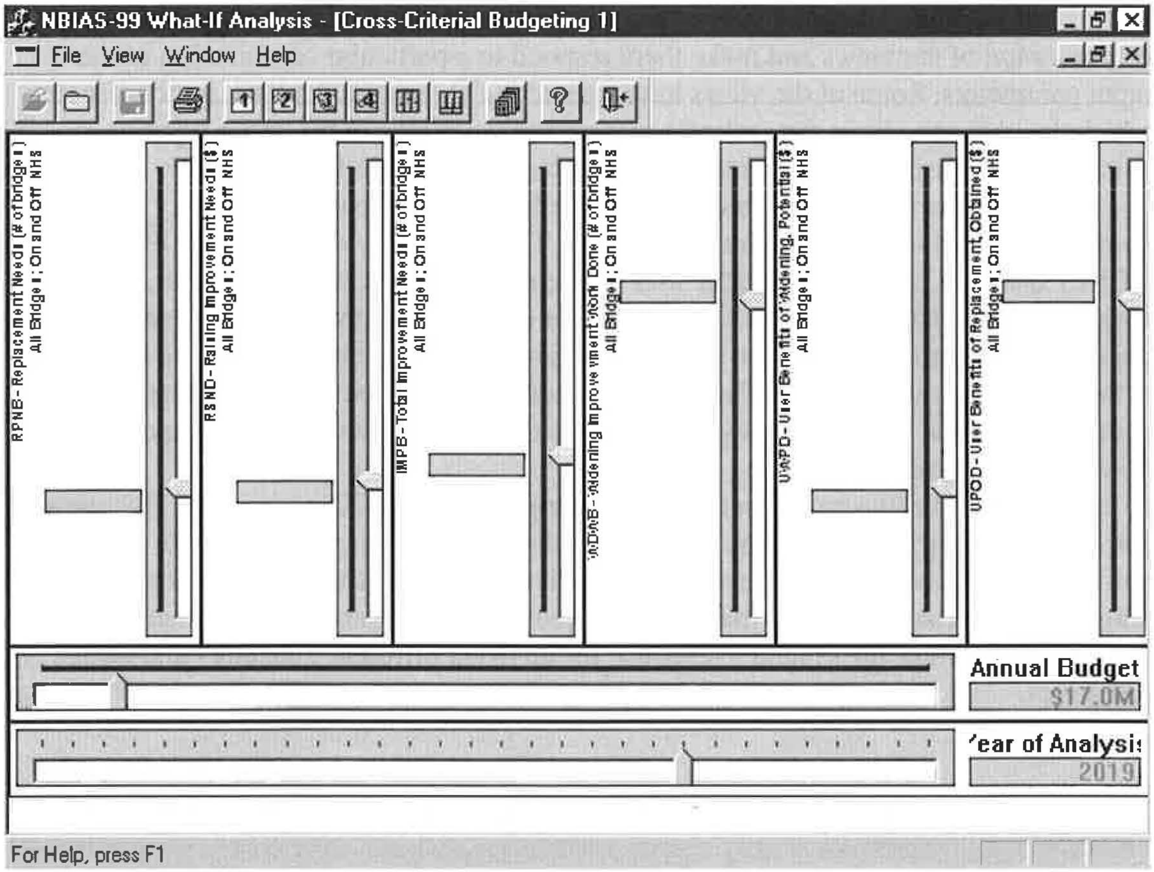


Figure 1: Budget targeting view.



Annual Budget $17.0M

'ear of Analysi: 2019

Figure 2: Cross-criteria view.

In total, NBIAS and PLANOPT each have six different types of the views and four different forms of reports. Multi-document style of the "What-If" application module allows the user to work with several views and reports simultaneously.

CONCLUSION

Two national bridge management systems, PLANOPT and NBIAS, follow a common concept. The essential moments of this concept can be summarized as parametric simulation of the budget allocation process, multiple measures of effectiveness, stratification of the bridge inventory and interactive "What-If" analysis. The level of abstraction provided by the concept is high enough to allow wide variation of methods, models and criteria to be applied in either specific system. Differences in the approaches and organizational processes that exist between the U.S. Federal Highway Administration and the Swedish National Road Administration are reflected in the methodological parts of NBIAS and PLANOPT. At the same time, the results of the simulation processes performed in the systems converge to the general form to which common methods of "What-If" analysis are applied.

In both organizations, implementation of a policy decision support tool is highly anticipated. The ability to have literally thousands of possible plans "pre-solved" when working with the user interface will allow agencies to consider a wider range of plans from a number of perspectives that are currently too time-consuming to consider mathematically. The expectation is that the improvements that NBIAS and PLANOPT will make to their respective planning processes will help the agencies involved make more informed decisions on the allocation of national funds for bridge maintenance and functional improvements.