Multi-Period Bridge Investment Optimization Utilizing Pontis Results and Budget Constraints by Work Type

Word Count: 5,704 + 6 figures/tables * 250 words/figure or table = 7,204 words

William E. Robert and Dmitry I. Gurenich
Cambridge Systematics, Inc.
100 CambridgePark Drive, Suite 400
Cambridge, MA 02140
tel: (617) 354-0167
fax: (617) 354-1542
email: wrobert@camsys.com, dgurenich@camsys.com

Richard E. Thompson
Virginia Department of Transportation
1401 East Broad Street
Richmond, VA 23219
tel: (804) 786-1024
fax: (804) 786-7787
email: richard.thompson@vdot.virginia.gov
ABSTRACT

One use for a bridge management system (BMS) is to optimize allocation of funds and predict future conditions given a set of funding constraints. The Virginia Department of Transportation (VDOT) uses the American Association of State Highway and Transportation Officials (AASHTO) Pontis BMS for this purpose. A critical limitation VDOT has encountered in using Pontis is that the system offers no functionality for specifying the budget by work type when performing a program simulation. This paper describes an approach developed by Cambridge Systematics for VDOT for using results generated by Pontis to optimize bridge investments over a ten-year period considering budget constraints by year for each of five work types. The approach entails performing a series of Pontis simulation runs as a one-time or occasional step, and then performing a secondary optimization with work type constraints. Two VDOT-owned systems have been developed to support the approach described here. The VDOT Pontis Robot connects to the VDOT Pontis database and performs a series of eleven Pontis simulations. Once the VDOT Pontis Robot has been run, then the VDOT Post-Pontis Optimizer can be used to optimize bridge investments for one or all VDOT districts. Performing an optimization requires approximately 5 seconds. While the approach described here leverages the Pontis BMS, it nonetheless represents a significant improvement to Pontis through implementing multi-period optimization, budget constraints by work type, and real-time generation of budget optimization results.
INTRODUCTION

One use for a bridge management system (BMS) is to optimize allocation of funds and predict future conditions given a set of funding constraints. The Virginia Department of Transportation (VDOT) uses the American Association of State Highway and Transportation Officials (AASHTO) Pontis BMS for this purpose. In recent years VDOT staff have invested considerable time refining the models in Pontis to improve their ability to obtain realistic results from the system. A critical limitation VDOT has encountered in using Pontis is that the system offers no functionality for specifying the budget by work type when performing a program simulation. Instead, when one runs a program simulation in Pontis, one specifies an overall budget constraint, and the system attempts to optimize the work recommended in any one year without regard to work type. VDOT bridge engineers have reported that the lack of functionality for specifying budget constraints by type of work is a significant shortcoming in the system, and limits the value of the system’s results.

This paper describes an approach developed by the authors for VDOT for using results generated by Pontis to optimize bridge investments over a ten-year period considering budget constraints by year for each of five work types. The approach supports VDOT’s approach to bridge programming, which involves determining the allocation of funds by district with funding constraints by work type. The resulting allocation is used to determine what bridges on which to perform work, given work on a bridge typically is performed no more than once every ten years. The approach entails performing a series of Pontis simulation runs as a one-time or occasional step, and then performing a secondary optimization with work type constraints. The preliminary Pontis simulations are used to specify alternative life cycle profiles for each bridge in the VDOT network, including a “do nothing” for each bridge. Once the simulations are completed, statistics are compiled for each bridge, including the costs, benefits and predicted performance for each candidate life cycle profile (also referred to as alternatives or project alternatives in this paper). The optimization step selects the set of life-cycle profiles that maximizes agency and user benefits, subject to budget constraints for each year and work type. Two VDOT-owned systems have been developed to support the approach described here: the VDOT Pontis Robot for automating Pontis scenario runs, and the VDOT Post-Pontis Optimizer for performing the optimization.

The following sections provide background on Pontis and relevant BMS research, detail the technical approach, described implementation of the Robot and Post-Pontis Optimizer, and present a series of conclusions.

BACKGROUND

This section provides supplemental background information on three topics relevant to the approach of the VDOT Pontis Robot and Post-Pontis Optimizer. Because these tools rely heavily upon output from Pontis, a brief summary of the technical approach of that system is provided. An incremental benefit-cost approach is used in Pontis to select the set of project to perform from a list of candidates. This approach is used in the Post-Pontis Optimizer as well, though with additional constraints. Some background information is provided on incremental-benefit cost approaches. Finally, background information is presented on the pre-processing approach used in a number of what-if analysis systems and adapted for use by VDOT.

Pontis

The AASHTO Pontis Bridge BMS was initially developed through an NCHRP study funded by the U.S. Federal Highway Department (FHWA). Since 1994 Pontis has been supported and maintained through AASHTO. The modeling approach of Pontis is detailed in ([1]). There are two major components of its modeling approach: preservation policy optimization, and program simulation. The preservation policy is the set of recommended maintenance, repair and rehabilitation actions for each state of each condition unit that may exist on a structure, where a condition unit is defined as a combination of a bridge element and operating environment. The preservation policy is optimized by formulating a Markov decision model with the objective of minimizing discounted long-term agency costs.

The preservation policy, and additional parameters such as the agency’s budget, functional improvement policies, and standards, are used as inputs to the program simulation. The program simulation recommends preservation and functional improvement projects for each bridge in a network. The simulation uses an incremental benefit cost heuristic to select the set of projects to perform in any one year to maximize benefit, subject to a budget constraint. In performing the simulation, the system simulates one year at a time, selecting a set of projects for that year,
simulating their effects and the effects of deterioration, and then proceeding to the next year in the analysis period. Note that the simulation allows for a single budget constraint for each year.

Initially Pontis was designed to calculate benefits in terms of reduced agency costs relative to deferring action for one year (predicted through the preservation optimization) and reduced user costs for functional improvements. An issue with this approach was that agency benefits could be calculated only for actions recommended by the system. User-defined projects with a scope greater than that recommended through strict application of the preservation policy tended to show disbenefits. A major change to the system introduced through Pontis Version 4.0 in 2001 was to allow end users to specify a set of agency rules for supplementing, overriding or completely replacing the Pontis preservation policy. The motivation for this change is detailed in (2). In conjunction with the addition of agency rules, the benefits measure was changed to calculate agency benefits on the basis of the difference in Health Index that would result from performing the project relative to not performing the project in the analysis year. Health Index is a measure of the physical condition of the bridge, with 100 representing a bridge with all of its structural elements in the best defined condition state, and 0 representing a bridge with all of its elements in the worst defined state, as detailed in (3). By default the Health Index change is multiplied by a measure of bridge value to predict the additional value attained by performing the recommended work. This proxy for agency benefits is added to the user benefit to calculate the total benefit of a candidate projects. An adjustment factor is provided for specifying the weight on user benefits versus agency benefits.

Incremental Benefit Cost

The problem of selecting the set of projects that maximizes value is a variant of the Capital Budgeting Problem (4). McFarland, et. al. (5) developed a specific incremental benefit cost heuristic termed “INCBEN” as a computationally efficient approach to recommend a near-optimal solution to this problem in cases with multiple, mutually exclusive project alternatives. Subsequently Farid, et. al. (6) described implementation of this approach for bridge management. Patidar, et. al. (7) provides additional background on other solution approaches for bridge management.

The specific heuristic detailed in (5) works as follows when applied to a set of assets, each of which may have multiple, mutually-exclusive project alternatives:

- The set of mutually exclusive project alternatives is defined for each asset.
- For each asset the alternatives are ordered by increasing cost.
- If a given alternative has benefit less than or equal to that of another alternative with the same or less cost, the alternative is discarded.
- The incremental benefit-cost ratio (IBCR) for each alternative is calculated as the difference in benefit divided by the difference in cost of the alternative compared to the next less costly alternative. The least costly alternative is compared to the “do nothing” alternative. Thus, its IBCR is equal to its benefit-cost ratio (BCR).
- The IBCR values are examined to verify that the benefit function is well-behaved (i.e. IBCR decreases as cost increases, which implies that the curve of benefits, plotted as a function of costs, is concave). In cases where a higher incremental benefit follows a smaller one, the two are averaged. This process is repeated until the benefit function is well-behaved. If the benefits measure is monetized consistently with costs, then incremental benefits should exceed incremental costs for each alternative, or the alternative should be discarded.
- The IBCR values for all assets are combined into a single list and sorted in decreasing order.
- Projects are selected from the list until the budget constraint is reached.

Figure 1 shows an example of an IBCR calculation performed as described in (5). In this example, there are three alternatives: A, B, and C. Initially the IBCR is calculated as 3.0 for A, 1.0 for B and 3.0 for C. However, as C has greater cost and greater IBCR than B, the IBCR values for B and C are averaged to obtain a value of 2.0 for both alternatives. Without this step, the project selection process would result in selecting B if funds are unlimited. With this revision, A is selected initially, followed by B, then C if funds are sufficient. Note that substituting in different IBCR values for B and C while keeping their costs fixed implicitly shifts the benefits for these alternatives. However, if either is selected, the actual benefits are used, not the benefits implied by the recalculated IBCR.
Conceptually incremental benefit cost approaches such as the described above can be used with any benefit measure. McFarland, et. al. (5) described using accident reductions and other benefit measures with the approach. Sobanjo expanded upon this concept, detailing how to use a utility function as the measure of benefit in implemented an incremental benefit cost approach (8). Recently Patidar, et. al. performed further testing of incremental benefit cost approaches, reconfirming McFarland’s findings, and expanded upon Sobjanjo’s use of incremental benefit cost with a utility function, providing a set of spreadsheet tools demonstrating use of an incremental benefit cost approach to solve a multi-objective problem (7). Though none of the prior examples describe an incremental benefit cost application with multiple budget constraints, the approach has been implemented with such constraints, such as in recent work by the authors for the Ministry of Transportation of Ontario described below. Given the extensive use of this optimization heuristic in the past, the incremental benefit cost approach was a logical choice for program optimization in the VDOT Post-Pontis Optimizer.

Preprocessing for What-If Analysis

Minimizing computation time is an important objective in the design of bridge management systems and tools. Computer processor speeds have continually increased over time, reducing operations that 20 years ago would have required hours down to a few minutes or less today. However, BMS computations can still be rather time consuming, particularly when they require storing and retrieving large amounts of data to and from relational databases. For example, running a program simulation in Pontis for the over 20,000 bridges in the VDOT database requires over an hour of time on a typical personal computer. Given any change in capital programming parameters requires rerunning the program simulation. Pontis can be a rather cumbersome tool to use for what-if analyses requiring repeated changes to budgets and other assumptions. This issue is representative of that of many management systems that rely upon simulation processes.

A basic approach to working around computation time issues inherent where large scale simulation is used is to run a series of simulations in advance of the end user’s accessing the system, and preprocess the result to support rapid response to parameter changes made at runtime. Gurenich described such an approach and illustrated its implementation in the National Bridge Investment Analysis System (NBIAS) for FHWA and Planopt for the Swedish National Road Administration (9). Both of these systems simulate a range of different budget levels in advance. Then, the user interacts with the system through a set of dynamic views that allow the user to vary the budget and analysis scope in real time. Subsequent to developing NBIAS and Planopt Gurenich developed the Executive Support System (ESS) for the Ministry of Transportation of Ontario. This system includes a Pre-Processor that uses an incremental benefit cost approach to simulate outcomes for a range of different budgets, including an overall budget constraint, as well as constraints by asset type and/or geographic area.

The same basic approach as that used in NBIAS, Planopt and the ESS was implemented in developing the AssetManager suite of asset management analytical tools (10). In addition, AssetManager includes a robot application for running multiple simulations in Pontis over a range of different budget levels using the Pontis Application Programmer Interface (API) described in (1).
TECHNICAL APPROACH

This section describes the technical approach of the VDOT tools, detailing how previous work on Pontis, incremental-benefit cost approaches and preprocessing simulation results to support what-if analysis was leveraged to develop the VDOT Pontis Robot and Post-Pontis Optimizer. The following subsections present the model formulation, describe how Pontis results are used, and discuss the optimization approach.

Model Formulation

The optimization problem the VDOT Post-Pontis Optimizer solves may be expressed as follows:

\[
\max \sum_{i} \sum_{j} \delta_{ij} U_{ij}
\]

such that

\[
\forall \sum_{j} \delta_{ij} = 0
\]

\[
\forall \sum_{j} \delta_{ij} = 1
\]

\[
\forall \sum_{k} \sum_{j} \delta_{ij} C_{ij}^{kl} \leq B^{kl}
\]

where

- \( \delta_{ij} = 1 \) if alternative \( j \) is programmed for bridge \( i \), 0 otherwise
- \( U_{ij} \) = benefit (utility) of alternative \( j \) for bridge \( i \)
- \( C_{ij}^{kl} \) = cost for work type \( k \) in period \( l \) of performing alternative \( j \) for bridge \( i \)
- \( B^{kl} \) = maximum budget for work type \( k \) in period \( l \)

As indicated in Equation 1, the objective of the problem is to select the set of alternatives that maximizes benefit subject to a set of budget constraints specified by funding period and work type. Each alternative has assigned to it a benefit or utility and set of costs by work type and period. Conceptually, the alternative could be a single project or life cycle profile that includes a set of actions over time. It is assumed that one and only one alternative can be selected per bridge for the analysis period.

The formulation uses a definition of benefits consistent with that of Pontis, though modified to account for the fact that a single optimization is performed for the entire analysis period, rather than having a series of optimizations performed sequentially for each period. Thus, the agency benefit is calculated as the difference between the average health index as of the end of the analysis period with and without the project, multiplied by total element value as described in (1). The user benefit is calculated for each year of the analysis period as described in (1), and the discounted sum of benefits for each year is used for this component of the benefit. A weighting factor is provided to allow the end user to determine how user benefits should be weighted relative to agency benefits.

VDOT has specified five work types for the analysis: preventive maintenance, restorative maintenance, painting, rehabilitation and bridge replacement, and specified how the element and bridge action types in Pontis map to these work types. In VDOT’s case, preventive maintenance includes actions such as deck sealing, thin deck overlays and joint repairs. Restorative maintenance includes rigid deck overlays, superstructure repairs and substructure repairs. The model formulation supports either explicitly tracking the cost incurred by each work type, or treating all of the...
work for a given alternative as being for a particular type. VDOT’s business practice is to classify a bridge project as being of one of the five types listed above. Where a project consists of multiple types of work on different elements, it is classified based on the predominant (most expensive) work type.

Utilization of Pontis

The Pontis BMS is capable of calculating all of the data required to support the model formulation presented above. Pontis stores details on the work considered for each element of each bridge included in a program simulation, as well as bridge-level performance measures. The detailed work data can be used to calculate work costs, classification of work by type, and user benefits. Supplemental analysis of bridge-level performance measures is needed to calculate Health Index and other performance measures.

In order to utilize Pontis results for a ten-year analysis period, it is necessary to run eleven program simulations in Pontis. The first simulation is a “do nothing” scenario in which no work is programmed. Alternatively, agency rules can be employed to formulate this scenario as a “do minimum” scenario in which only certain types of actions are allowed. For each of the ten remaining simulations, an unlimited budget is defined for one year, and no budget is specified for the other years of the analysis period (e.g., for Scenario 2 the budget is unlimited in Year 1 but zero in Years 2 to 10, for Scenario 3 the budget is unlimited for Year 2 but zero for Year 1 and Years 3 to 10, etc…). Thus, the results for a simulation describe a life cycle profile for each bridge in the inventory.

Following the completion of the simulation runs, performance measures are tabulated for each alternative, and the set of candidate alternatives is assembled for use in the optimization process described below.

Optimization Approach

The authors explored solving the optimization problem as an integer programming problem, but in the interest of minimizing computation time, ultimately elected to use the incremental-benefit cost approach identical to that detailed in (5) recommended through prior research. Where this approach is used with multiple budget constraints, the selection of alternatives proceeds as described previously, from highest IBCR to the lowest until the budget constraints are met. If selecting an alternative violates any of the budget constraints, the alternative is skipped, and the process proceed to the next alternative.

A concern in using the incremental benefit cost approach described in (5) is that this heuristic approach was not designed to handle multiple, inter-temporal budget constraints, and the model formulation, with a set of 50 budget constraints (five work type constraints for each of ten years) rather than one, may test the limits of the approach for producing near-optimal results. Generally, the favorable performance of incremental benefit cost approaches is explained by pointing out that only at the end of the budget allocation process, in selecting the last few project alternatives to fund, is it possible to construct scenarios in which one may obtain suboptimal results. With additional budget constraints, there is additional potential for suboptimal alternative selection. Further, though the value of an incremental benefit cost approach is in its handling of cases in which there are multiple, mutually-exclusive project alternatives for an asset, in point of fact in systems such as Pontis there is typically only one alternative defined for a bridge, and the heuristic resolves to simple allocation of funds by BCR. In this case, the nuances related to ensuring the benefit curve are well-behaved are not put to the test. However, in the application described here, with up to eleven alternatives defined per bridge, any distortions introduced by handling of mutually-exclusive alternatives and the calculation of IBCR are of concern.

To determine how best to solve the optimization, four optimization approaches were tested. They included:

- Approach 1 - Year-by-Year, in which the optimization is performed once for each analysis period, deferring further work on a bridge if work was selected in a prior period;
- Approach 2 - Interpolation, in which the basic incremental benefit cost approach detailed in (5) and described above is used, with the exception that rather than averaging IBCR values, the IBCR for the alternative with the greater benefit is recalculated assuming the lesser is excluded, and the IBCR is linearly interpolated based on the IBCR values for the next less expensive and more expensive alternatives;
- Approach 3 - Exclusion, in which alternatives with a poorly-behaved IBCR are simply omitted from the analysis; and
Approach 4 - Multiple Curves (MINCBEN), in which the IBCR calculation process is performed multiple times, resulting in a set of well-behaved benefit curves rather than excluding or averaging IBCR values where the benefit curve is poorly-behaved.

Approaches 1 to 3 are simple variants of the approach described in (5). The authors could find no reference to an approach such as that described in Approach 4 in their review of the transportation asset management literature. This approach was implemented as follows:

- The set of mutually exclusive project alternatives is defined for each asset.
- For each asset the alternatives are ordered by increasing cost.
- The incremental benefit-cost ratio (IBCR) for each alternative is calculated as the difference in benefit divided by the difference in benefit of the alternative compared to the next less costly alternative. The least costly alternative is compared to the "do nothing" alternative. Thus, its IBCR is equal to its benefit-cost ratio (BCR).
- The IBCR values are examined to verify that the benefit function is well-behaved (i.e. IBCR decreases as cost increases, which implies that the curve of benefits, plotted as a function of costs, is concave). In cases where a higher incremental benefit follows a smaller one, the alternative with the smaller IBCR value is removed from the set of alternatives, and reserved for further consideration. The IBCR is then recalculated for the remaining alternative.
- After the set of alternatives for the asset is examined, analysis proceeds to the reserved set.
- The preceding three steps - recalculating IBCR, examining the benefit function, analyzing the new reserved set - are repeated until multiple sets of alternatives have been defined for each asset, each set having a well-behaved benefit function.
- The IBCR values for all assets and alternative sets are combined and sorted in decreasing order.
- Projects are selected from the list of alternatives until the budget constraints are met. An alternative is skipped if selecting the alternative would violate a budget constraint, or if a selection has been made from a different alternative set for the same asset.

Note that Approach 1, with only one alternative defined per bridge per period, reduces to a set of sequential BCR optimizations, and is most comparable to how Pontis would operate with no changes other than to include work type constraints. Figure 2 illustrates how IBCR is calculated for Approaches 2 to 4 for the example of a single asset shown in Figure 1. As implied by the figure, with Approach 2 – Interpolation, alternatives are selected in order of increasing cost, from A to B to C. In Approach 3 - Exclusion, either A or C is selected and B is excluded. For Approach 4 – Multiple Curves, the process initially considers A, or B if A is not selected. C is then considered only if B was not selected. Given B is more expensive than A, with a single budget constraint B would never be selected and Approach 4 would be equivalent to Approach 3. But with multiple budget constraints, it is feasible that any of the three alternatives would be selected using this approach.

Figure 2. IBCR Calculation Examples for Interpolation, Exclusion and Multiple Curves

The four approaches were tested for the following four budget scenarios:

- Scenario 1 - High Budget, the budget was set to be the same for each period, at a level sufficient to fund work for approximately half of the bridges with recommended work;
- Scenario 2 – Low Budget, the budget was set to be the same for each period, at a level sufficient to fund work for less than a quarter of the bridges with recommended work;
• Scenario 3 – Varying Budget, the budget was set to vary randomly between the limits set for Scenario 1 and 2; and
• Scenario 4 – Unlimited Budget.

Table 1 presents the benefits obtained using the four optimization approaches for each of the four scenarios defined above. The benefits are presented in terms of the percentage of the maximum benefit that would be obtained with no budget constraints. Table 2 presents the percent of the budget expended for Scenarios 1 to 3, calculated as the sum of the funds allocated across all periods and work types divided by the sum of the budget constraints (the maximum allocation).

Table 1. Optimization Results for Benefits Obtained

<table>
<thead>
<tr>
<th>Optimization Approach</th>
<th>Percent of Maximum Benefits Obtained by Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 – High Budget</td>
</tr>
<tr>
<td>1 – Year-by-Year</td>
<td>42.8%</td>
</tr>
<tr>
<td>2 – Interpolation</td>
<td>32.0%</td>
</tr>
<tr>
<td>3 – Exclusion</td>
<td>31.6%</td>
</tr>
<tr>
<td>4 – Multiple Curves</td>
<td>43.5%</td>
</tr>
</tbody>
</table>

Table 2. Optimization Results for Budget Spent

<table>
<thead>
<tr>
<th>Optimization Approach</th>
<th>Percent of Budget Spent by Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 – High Budget</td>
</tr>
<tr>
<td>1 – Year-by-Year</td>
<td>99.9%</td>
</tr>
<tr>
<td>2 – Interpolation</td>
<td>87.7%</td>
</tr>
<tr>
<td>3 – Exclusion</td>
<td>79.5%</td>
</tr>
<tr>
<td>4 – Multiple Curves</td>
<td>99.9%</td>
</tr>
</tbody>
</table>

The results of the testing indicate that Approach 4 – Multiple Curves yields the best results, both in terms of generating benefits and spending the available budget. The benefits for this approach are 1.5% to 3.2% higher than the next best approach, Approach 1 – Year-by-Year, for Scenarios 1 to 3. In the extreme case of unlimited funding, the benefits for Approach 4 are 7.8% higher than those of Approach 1, and equivalent to the benefits for the other two approaches. Approaches 1 and 4 out-perform Approaches 2 and 3 in Scenarios 1 to 3. Approaches 2 and 3 tend to leave more funds unspent, resulting in lower benefits.

One seemingly counterintuitive result is that Approach 1 performs better than Approaches 2 and 3 in most of the scenarios, and is almost as good as Approach 4. However, this result is not surprising when one considers that where the most benefit can be derived from performing work on a bridge as soon as possible, which is often the case, Approach 1 tends to behave similarly to Approach 4. Also, in the extreme case of an unlimited budget Approach 1 is the worst performing of the approaches. Based on the testing Approach 4 – Multiple Curves was implemented for use in the VDOT Post-Pontis Optimizer.

**SYSTEM IMPLEMENTATION**

The technical approach described in the previous section was implemented through a set of relational database stored procedures and two applications developed in Microsoft C#.NET: the VDOT Pontis Robot and Post-Pontis Optimizer. These applications connect to a Pontis 4.4 database, which may be either an Oracle or Sybase Adaptive Server Anywhere database, that has been supplemented with a set of VDOT-specific analysis tables and views.

The VDOT Pontis Robot (which is a different system from the AssetManager Pontis Robot) connects to a Pontis database and runs the required set of eleven program simulations. The user is required to supply their username and password, and to launch the analysis process. This system utilizes the approach to running Pontis initially developed as described in (10). Running this system requires approximately an hour for each of the scenarios on a typical personal computer connecting to a Sybase database. Post-processing of the results requires approximately 10 additional minutes. Running the Robot is a time consuming process, but in theory should be required only periodically, following updates to bridge condition or changes in agency preservation policies.
The VDOT Post-Pontis Optimizer connects to a Pontis database for which the Robot has previously been run. The user selects whether to perform an analysis for all of the bridges in the inventory, or for the bridges in a particular district. He or she then specifies the budget constraints for each work type and year and runs the optimization, after which the system optimizes and present its results. The user can then review the results through viewing a summary report, repeat the optimization with different scope or constraints and/or save the results back to the database to support further reporting and analysis. Running each optimization requires approximately 5 seconds on a typical personal computer.

Figure 3 is a screen shot of the budget constraint specification screen. Figure 4 is a screen shot showing summary results. Note that the budget constraints and results shown in the figures are provided for illustrative purposes only.
CONCLUSIONS

The approach described in this paper has been implemented to provide VDOT with a system that uses results from the Pontis BMS to optimize bridge investments over a ten-year period considering budget constraints for each of five work types. In implementing this approach the authors have tested different incremental benefit cost for capital budgeting optimization, resulting in selection of a variant that performs the IBCR calculation step multiple times, resulting in multiple benefit curves for an asset, as an alternative to averaging or interpolating IBCR values. Two systems have been developed and implemented as part of this effort, the VDOT Pontis Robot and Post-Pontis Optimizer.

This study demonstrates the use of Pontis BMS results to facilitate supplemental analyses, and represents a significant improvement to Pontis through implementing multi-period optimization, budget constraints by work type, and real-time generation of budget optimization results. Nonetheless, this study suggests a number of areas where further research may be justified to further improve the approach and bridge management systems in general. These include.

- Determining how sensitive the results are to variations in budgets between work types, redefining work types, and changing the business rules concerning how alternatives with multiple work types on different elements should be classified.
- Evaluating how well the Health Index-based benefits predicted by Pontis and used here serve as a proxy for the full range of costs related to bridges incurred by bridge owners and society, including costs related to the risk of bridge closure.
- Reconsidering whether the optimal preservation policy recommended by Pontis is, indeed, optimal. This policy makes a number of assumptions that appear fallacious in the case of VDOT, given its business rules. For example, the Pontis approach implicitly assumes that there is no interdependence between elements, that work can be performed on a small fraction of an element’s quantity, and that if work is not performed in a given period, the alternative is to defer work for one year.
- Testing the sensitivity of the results to changes/uncertainty in costs, the discount rate, fuel costs, traffic, bridge failure rates, potential changes in functional policies and other parameters.
- Exploring whether using other optimization methods to obtain an exact solution would significantly improve the results. At a minimum, this step should be performed to test the quality of the solution. Although such an
approach would be more time consuming, recent experience by the New Brunswick Department of Transportation in implementing an integer programming for performing a multi-period optimization of its pavement and bridge investments using Remsoft’s Woodstock system suggests it is possible to reduce integer program computation times to an acceptable level for capital budgeting problems.

ACKNOWLEDGEMENTS
The authors wish to acknowledge the Virginia Department of Transportation for its support of the research described in this paper.

REFERENCES
5. McFarland, W., Rollins J., and Dheri, R., Documentation for Incremental Benefit-Cost Technique, Program INCBEN. Technical report prepared for the FHWA by the Texas Transportation Institute, Texas A&M University, College Station, TX, December 1983.