Proceedings of the 2002 Winter Simulation Conference
E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, eds.

EVALUATION OF POLICIES FOR THE MAINTENANCE OF BRIDGES USING DISCRETE-EVENT SIMULATION

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ABSTRACT

The complexities and costs associated with preserving the nation's bridge infrastructure demand innovative approaches to analysis of data and prediction of future bridge conditions. Several Bridge Management systems (BMS) have come into existence following the ISTEA act of 1991. The policy analysis module of BMS systems developed is restricted to analytical methods. With the availability of modern infrastructure, realistic simulation models are being developed in several fields. This leads to the question of whether reasonably realistic and practical discrete event simulation (DES) based policy analysis tools can be developed? A DES model was developed for the Salem district of Virginia using a simulation language, STROBOSCOPE. This simulation model can be used to simulate the bridge network behavior under different policies and observe the impact on the health of the network making it a useful tool for decision-making. The tool enables the formulation and testing of different bridge maintenance policies.

1 BACKGROUND

The key components of a Bridge Management system are the data storage module, deterioration models, cost models and the policy analysis tool. These four components integrate seamlessly to provide the decision maker with the ability to make decisions, pertaining to maintenance and improvement that take into account both the financial constraints as well as the overall needs of the highway system.

Of the four components of the bridge management system, the policy analysis tool is the "brain" of the system. It is responsible for directing the other three modules and providing the decision maker with an effective means to compare different policies and determine the best policy to be followed. Several tools have been developed to aid the decision makers in allocating the funds among the competing needs (Kleywegt and Sinha, 1994). Some of the common techniques in use are priority setting and optimization specifically linear programming, dynamic programming and integer programming techniques.

A policy analysis tool that uses analytical techniques like optimization is inherently limited by several factors. Such a tool will be computationally demanding and might require huge analysis times thereby limiting its use. Also any such tool cannot handle distributions of data that are inherent in real life. The randomness in estimating a variable quantity like the cost of a maintenance activity or its duration is lost and could lead to uneconomical results. "Uncertainties can easily lead to making the wrong decisions, especially in selecting the best from pairs of closely ranked competing strategies" (Sobanjo, 1999). Discrete Event Simulation is a tool that can effectively handle probabilistic distributions of data. However any realistic simulation model is computationally demanding thereby limiting its use to date due to lack of available technology. With the advances of computational power in the last decade, it has been made possible to develop and test realistic simulation models, which will help the decision maker to capture all the inherent uncertainty in the data and yet to a reasonable level of reality simulate the scenarios.

The motivation for this research was to explore the possibility of DES as a Bridge Management Policy Analysis tool and to determine the nature of data requirements for such a model, the kind of policies that can be modeled and simulated and finally the effectiveness of such a model. Further the practicality of the tool dictates that it generates results quickly so that the user can try out different scenarios immediately.

The goal of this research was to develop a DES based policy analysis tool. The simulation tool will query the user for the available funds and the kind of policy to be implemented for bridge maintenance and predict the network health over a period of time. The user can simulate the effect of different alternatives on the system and decide on an optimal funding policy based on the results. The development of any such tool would sufficiently address the issues raised above.

2 DEVELOPMENT TOOLS

For the purpose of testing and simulations, the interstate bridges of Salem district of Virginia were chosen. All the relevant data and models were extracted from the Salem Bridge management system - Pontis database. A total of 102 interstate bridges on I81 were simulated. The simulation model was then developed in using Stroboscope. Some extensions had to be made to the model for it to interface with Pontis. These extensions were developed in C++ using Microsoft Visual Studio – version 6.

3 SIMULATION OF THE BRIDGE MANAGEMENT PROCESS

3.1 Bridge Selection

The bridges in a network are not identical but each one has its own properties. At any given point of time each bridge has its own needs and competes for resources. Though each bridge is unique, a common platform needs to be developed in order to compare the competing bridges and ensure maximum benefit for the resources consumed. The need to have a single number that could be used to judge the performance of maintenance and rehabilitation efforts was identified by California Department of Transportation. They have developed a performance measure called the health index (HI), which ranks a bridge on a scale of 0 to 100 (Roberts and Shepard, 1992).

Though the HI provides an effective mechanism to compare different bridges and rank them accordingly, merely selecting the bridges with the lowest HI for maintenance does not mimic reality. In order to ensure effective utilization of the available resources a mechanism called the Improvement Cost (IC) ratio has been developed. The IC ratio is defined as

$$\text{Improvement Cost Ratio} = \frac{\text{Future HI} - \text{Current HI}}{\text{Cost of Maint. Action}}$$

where the Future HI is the new health index the bridge will achieve if the proposed maintenance action is performed, Current HI is the HI of the bridge before the maintenance action is performed and Cost of Maint. Action is the total cost of the proposed maintenance action.

Using the element level policies the overall IC for the bridges are developed every year. The bridges are then ranked in descending order of their IC ratio. Based on the available funds the bridges are selected from the top until the model runs out of funds thereby ensuring maximum improvement for the resources consumed. If the model encounters a situation where the available funds are insufficient for the bridge under consideration in the list, the model proceeds down the list to see if it can perform maintenance activity on a bridge with lower IC ratio thereby utilizing all the available funds.

3.2 Working of Simulation Model

The understanding of the bridge management process was obtained through literature review and interviews with experts. This understanding was then translated into a simulation model. The front end of the simulation model is given in figure 1.

The *BridgesToCreate* node is where the bridges in the network are created. Here the bridges are a simple place holder for the elements and do not contain any information other than Bridge ID. The *ElementToCreat* is where the individual elements of the bridge are created. The elements contain the inspection data and deterioration conditions. The *CreateBridges* node matches the bridges to the corresponding elements and creates whole bridges. At this stage the bridge properties like number of elements, overall health index (HI) of the bridge are determined. The bridges and their corresponding elements are combined together in the *AssembleBridges* node as a unit. At this stage the Bridge component contains the individual element components and the two are inseparable. Once assembled the individual elements cannot be accessed directly. Only the Bridge properties are available at this stage. This feature is used to group together all the elements of a bridge together and work on them as a bridge unit instead of the individual elements. It also helps to compare bridges instead of individual elements of a bridge. At this stage the bridges pass on to the *BridgeNetwork* node where they reside for the rest of the duration of the simulation. This concludes the initialization phase of the model and at the end of this stage the bridge network with all the relevant information has been created.

The *RepairBridges* node draws the bridges from the network for repair and maintenance one by one. The total number of bridges that can be drawn for repair depends on the available budget, which can be changed every year. The link B4 connecting *BridgeNetwork* and *RepairBridges* is the link where decisions pertaining to which bridge to work on are taken. This is a crucial part of the simulation model since the network policies are what decide the behavior of the model. Once a bridge is selected it passes on to the *DisassemBridges* node, which separates the elements from the bridges so that they can be worked on. The *RepairElements* is where the elements are repaired and their condition, cost incurred and other parameters are updated. Also the available funds are deducted by the appropriate amount. Once all the elements of the bridge are repaired, the bridge can be reassembled.

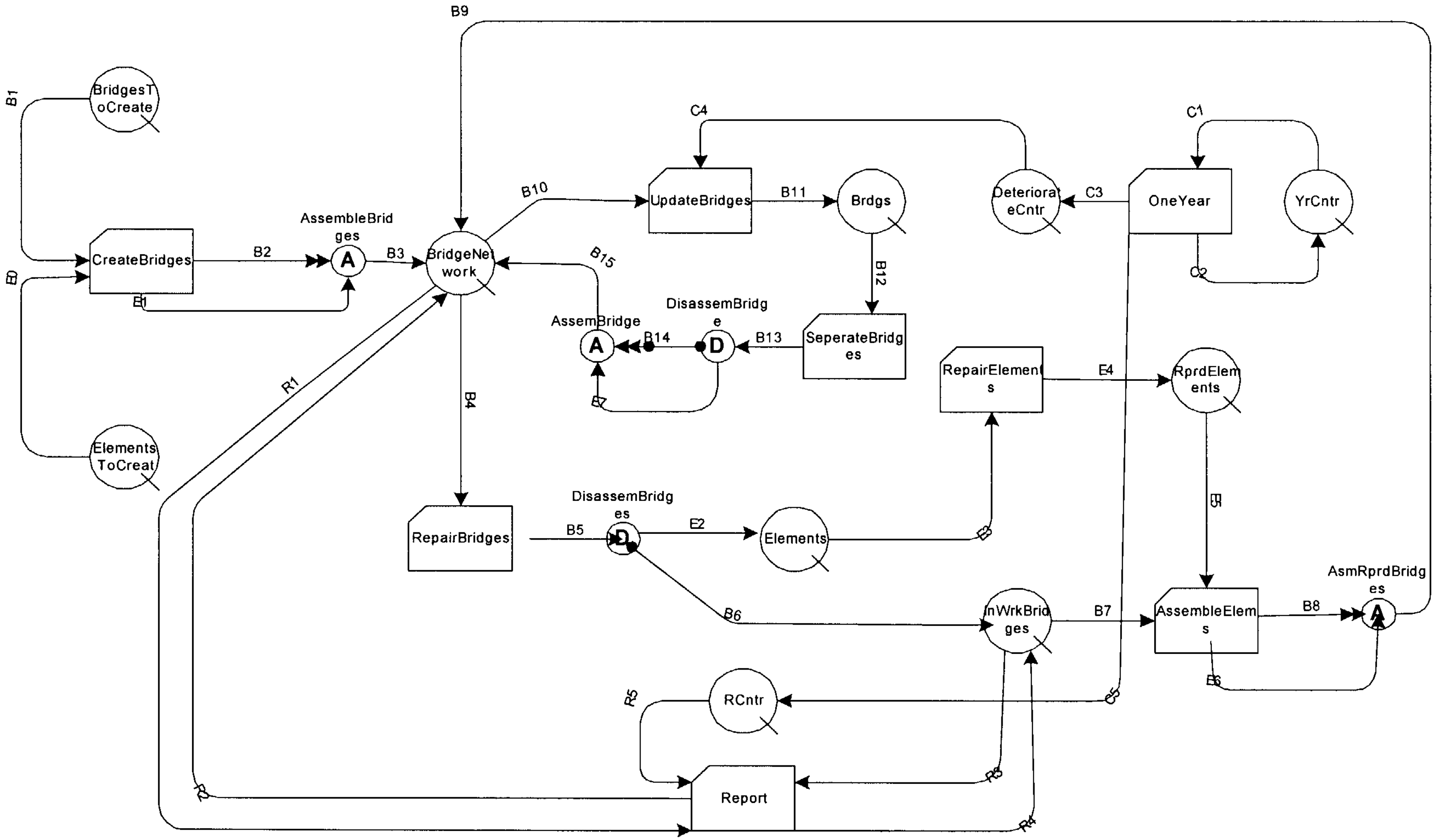

Figure 1: Front-End of the Simulation Model

AssembleElems matches the elements to the corresponding bridges and they are put back together in *AsmRprdBridges* and sent back to the *BridgeNetwork*.

If a bridge is not repaired then it deteriorates and its status needs to be updated. This updating of the bridges takes place at the end of every year. The loop *UpdateBridges*, *Brdgs, SeparateBridges*, *DisassemBridge*, and *AssemBridge* performs this action. The names of the nodes indicate the roles they play. The UpdateBridges selects the bridges whose condition needs to be updated. The Brdgs and SeparateBridges separate the bridges and send them one by one to DisassemBridge. The link E7 connecting DisassemBridge and AssemBridge updates the conditions of the elements. AssemBridge updates the bridge parameters (HI, RepairCost, etc.) based on the new element conditions. The DisassemBridge and AssemBridge update the deterioration of the node. The *YrCntr* and *OneYear* loop assures that the bridges are updated once every year.

Finally the Report draws the bridges every year and reports their status to the user.

3.3 Parameters of the Model

Based on the above behavior of the model the corresponding Stroboscope code was created and the appropriate Stroboscope statements were written. The following parameters can be modified to emulate different network scenarios.

YrsToSimulate	The number of years the network can be simulated.
FUNDSMTRX	The Budget assigned to each year
Delay	Minimum delay between successive repairs on a bridge
BridgeCount	The number of bridges that can be repaired simultaneously

3.4 Data Input from PONTIS (C++ dll)

Any simulation model needs realistic data to give meaningful results. In the design it was decided to segregate the Input data from the model. The advantage of this is that any changes made to the model will not affect the data and vice versa. The deterioration rates, costs and network policies are imported from PONTIS through the use of import facility provided in PONTIS. This information should be retrieved by the Stroboscope model. However Stroboscope was not equipped with the provision to extract data from an input file. So a DLL was developed in C++, which facilitated reading data from a text file and translated the information provided in the files for the simulation model to process. Then a set of functions were written which automated the process of reading the data from the text files and interpreting it accordingly and thereby driving the simulation model. The data has been imported from PONTIS in the Pontis Data Interchange (PDI) format.

The data is extracted by loading the DLL in the model and calling appropriate functions provided by the DLL. Once the information is extracted, the model proceeds with the simulation.

3.5 Policy Analysis File

The next step in the development of the model was the development of a suitable mechanism which would query the user the policies to be implemented in the simulation. For this purpose a Policy Analysis file was developed which would contain information about the preferred maintenance activities at the element level for each element encountered in the simulation. If any element of a bridge was then repaired, the specific maintenance action performed in the simulation would be based on the maintenance action for that element in the Policy Analysis file. The DLL provided the mechanism to load a policy analysis file. This is a simple text file with each element having a corresponding line as given below.

```
/ "Unp Conc Deck/AC Ovl"
13 0 0 0 2 1
```

The first line gives the PONTIS description of the element. The '/' indicates that the line is a comments line and should be ignored. The next line contains the actual policy information. The first number indicates the element to which this information belongs. The next five numbers indicate the preferred maintenance activity in each condition state. The '0' indicates a do-nothing activity, '1' indicates a maintenance activity type 1 corresponding to that condition state and similarly '2' corresponds to maintenance activity 2. Thus the unpainted concrete deck with AC overlay in condition states 1,2 and 3 do not get any maintenance activity performed, whereas maintenance activity type 2 is performed in condition state 4 and maintenance activity type 1 is performed in condition state 5. These element level policies need to be defined for all the elements. By varying the preferred activities, different policies can be implemented.

4 RESULTS

Based on the available database, several simulation test runs were performed to determine the validity of the model. The results are summarized in the graph in Figure 2. The NoMaintenance budget line is the network behavior under no maintenance budget and the currently used policies are represented in the Current Pontis line. The deck level and girder level policies are modified slightly to observe their impact on the network and it can be observed that the network health can be improved.

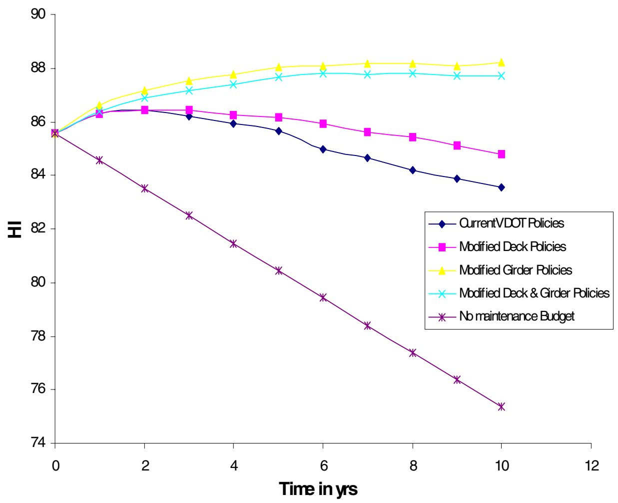

Figure 2: Comparison of Element Level Policies

This indicates the validity of the model and proves that discrete event simulation warrants a closer look as a policy analysis tool.

It should be noted that VDOT is currently in the process of redefining their PONTIS databases. Thus most of the information obtained from the PONTIS databases was not representative of the bridge conditions in Salem district. These results merely validate the model but no qualitative inferences should be drawn about the policies.

5 SUMMARY

Efficient management of the scarce resources is the most important challenge facing bridge management personnel today. Several researchers have developed policy analysis tools to help the decision makers manage the funds effectively and maintain bridges. The objective of this research is the development of a policy analysis tool using discrete event simulation, which serves as an instrument for predicting the network health under different scenarios to facilitate the Salem district Bridge system.

Effectively managing the different kinds of bridges and comparing them on a common platform is the first task in the development of such a tool. The CoRe element classification is an effective means of classifying the bridges into its elements to generate the probability and cost information. The HI is an effective measure of the bridge status based on the conditions of its elements rated using the CoRe classification. The second task is the comparison of different alternatives among the bridges and selecting the right bridges for maintenance to derive maximum benefit. For this a concept called the Improvement Cost ratio was developed similar to the Benefit Cost ratio used extensively in Asset management systems.

The policy analysis tool was developed using Stroboscope. The tool extracts the inspection data from the PONTIS databases. It also extracts the deterioration and cost models from PONTIS, though distributions can be developed for these models to capture the inherent randomness in assessing these values. The different kinds of policies that can be simulated are specified at the element level. The model queries the preferred maintenance activities for each element in every condition state. By altering these activities, different policies can be programmed into the model.

The simulation model can process PONTIS data and simulate the network. Therefore the existing methods of inspection are sufficient and the model does not have any additional data requirements. A few test simulations are run to demonstrate the working and validity of the model. It was observed that modifications of the policies could yield significant improvement in the network conditions. All the simulations were performed on a Pentium MMX processor with 96Mb RAM and Windows 2000 operating system. The simulations took less than a minute demonstrating the effectiveness of the tool. Several simulations can be run and analyzed almost instantaneously thereby bringing discrete event simulation into the realm of practical use for bridge policy analysis.

ACKNOWLEDGMENTS

This project has been supported by the Virginia Department of Transportation and the National Science Foundation. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of Virginia Department of Transportation or the National Science Foundation.

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