TOWARD AN OPTIMAL MAINTENANCE FRAMEWORK FOR DETERIORATING WATER DISTRIBUTION SYSTEMS

Yacov Y. Haimes and Duan Li
Center for Risk Management of Engineering Systems
University of Virginia

Introduction

In its landmark document titled Fragile Foundations: A Report on America's Public Works, which was submitted to the President and the Congress in February 1988, the National Council on Public Works Improvement stated:

> The Council Encourages renewed attention at every level of government to maintaining our current assets to optimum standards (emphasized by the Council). Maintenance is perhaps the single most important element of governments' stewardship obligation. It also is the element that is easiest to defer, and the one most likely to be cut from the current expense budget. Maintenance must be made more visible. This means providing understandable information on infrastructure conditions, performance, maintenance costs, and the annual amounts of deferred maintenance.

Water distribution systems epitomize the entire infrastructure rehabilitation and maintenance problem. Although the investment in the construction of water distribution systems in the United States is estimated at several billion dollars annually, the nation's water distribution system has been decaying rapidly; large capital expenditures are needed for its maintenance, modernization, and revitalization. Deteriorating water distribution systems experience high water losses because of leaks, and this results in wastage of energy and the possible contamination of drinking water through cracked pipes. These aging systems also cause many maintenance-related decisionmaking problems. For example, postponing critical maintenance decreases the reliability of existing systems and may cause catastrophic events, such as the numerous water failures that have occurred in many cities. Resources -- local, state, and federal — are not available to upgrade all systems completely; therefore, a method is needed to identify and prioritize critical locations where problems are likely to occur and to distribute limited resources optimally within the water distribution network.

Achieving the Council's goal of "maintaining our current assets to optimum standards" is a complex task. The complexity associated with the selection of an optimal replacement/repair strategy is due to the dynamic evolution of the failure modes of water mains, budget constraints, the large scale and intricacy that typifies most water distribution systems, and the competing and often conflicting demands placed by various constituencies on the use of these systems. All these factors make the development of a maintenance-related optimal decisionmaking framework a timely and appropriate response to an identified national need.

An Optimal Maintenance-related Decisionmaking Framework

A research project supported by the National Science Foundation (Division of Mechanical and Structural Systems, Program Director, Dr. John B. Scalzi) on optimal maintenance-related decisionmaking has been recently completed at the Center for Risk Management of Engineering Systems of the University of Virginia. The main research results are summarized in the following two subsections.

1. Optimal Maintenance-Related Decision-making for Deteriorating Water Distribution Systems: Semi-Markovian Model. The failure mode of a water main evolves in the deteriorating process. Research has indicated that the failure mode changes as a function of both time and the number of previous breaks (Andreou et al. 1987). Capturing the dynamic evolution of the failure mode is essential to achieving an optimal maintenance decision. Based on a two-stage model proposed by Andreou et al. (1987), a semi-Markovian model has been developed that includes various deteriorating stages of a water main as the system's state variable (Li and Haimes 1991a). At each operating state, the best maintenance policy is sought among a finite number of available period-age actions. According to a period-age policy, a pipe at an operating state may undergo a preventive replacement after a certain time period of continuous operation without break. At each nonoperating state, either the action of replacement or the action of repair needs to be taken. The cost and time distributions for actions of replacement and repair are based on a study by Walski and Pelliccia (1982). The output of the semi-Markovian decision model consists of the optimal actions at various deteriorating stages (Fig. 1).

The semi-Markovian model provides a decision aid for selecting the best replacement/repair policy at various stages of deterioration. There exist several distinct features of this decisionmaking model. Firstly, this model reflects the real Markovian property presented by deteriorating water pipes, where the failure mode of a deteriorating main pipe is a function of both time and the number of previous breaks. Secondly, the model captures the dynamic evolution of the failure mode of a deteriorating main pipe. Moreover, the probabilistic description can be incorporated with the repair/replacement process in the semi-Markovian model. The decision derived from this semi-Markovian model provides a balance between short- and long-term objectives, and it is thus superior to the myopic solutions derived from single-stage models.

2.Optimal Maintenance-Related Decision-making for Deteriorating Water Distribution Systems: Optimal Resource Allocation using a Multilevel Scheme. A water distribution system often consists of a large number of components. However, resources are in general not available to completely update all the deteriorating water pipes. Limited resources have to be optimally distributed among the system's components in order to achieve the highest systems availability.

It is generally a difficult task to allocate a limited resource among various systems components (or subsystems) in order to yield maximum availability. The formulated nonlinear programming problem related to such an optimal resource allocation is hard to solve as a whole because of its high dimension. The problem is also nonseparable in the sense of multilevel decomposition.

A three-level decomposition solution scheme has been developed by Li and Haimes (1991b) in which multiobjective optimization serves as a separation strategy. The nonseparable resource alloca-

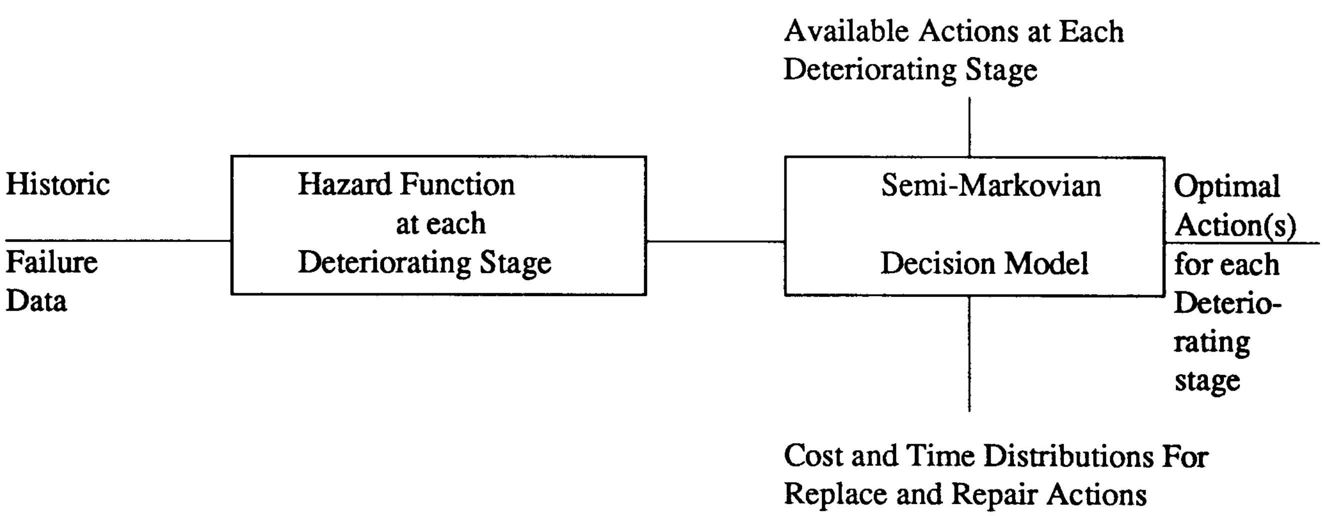

Figure 1. Input and Output of the Semi-Markovian Decision Model

tion problem for a deteriorating water distribution system was embedded into a separable, albeit multiobjective, resource allocation problem of a type easy to solve by a decomposition method. The optimal solution of the original nonseparable resource allocation problem was sought interactively in the set of noninferior solutions of the corresponding multiobjective problem. Each water main is described by a semi-Markovian model. This information and information about the network structure constitute the input for the multilevel decomposition solution scheme, which in turn generates the optimal actions at various deteriorating stages for all systems components (Fig. 2). One important product of this three-level decomposition approach is that it gives an importance measure for each system component, and this importance measure provides the priority rank for the maintenance of various system components. With the use of the importance measure, the manager of the system is able to determine the prioritization of the scheduled maintenance and replacement work on a scientifically based evaluation.

Epilogue

The increasing number of publications on the subject of optimal maintenance for deteriorating water distribution systems indicates a grass-roots awareness of its research importance. Much of the research, however, is still in a preliminary stage, and many challenging problems, both theoretical and methodological, need to be explored. There is a growing consensus that the systems approach will continue to play a major role in understanding the complex issues involved in such research in order to realize the Council's goal of "maintaining our current assets to optimum standards."

References

Andreou, S.A., D.H. Marks, and R.M. Clark. 1987. A new methodology for modelling failure patterns in deteriorating distribution systems: Theory. *Adv. Water Resources* 10:2-10.

Li, D., and Y.Y. Haimes. 1991a. Optimal maintenance-related decisionmaking for deteriorating water distribution systems, part 1: Semi-Markovian model. Accepted for publication, *Water Resources Research*.

Li, D., and Y.Y., Haimes. 1991b. Optimal maintenance-related decisionmaking for deteriorating water distribution systems, part 2: Multilevel decomposition approach. Accepted for publication, *Water Resources Research*.

National Council on Public Works Improvement. 1988. Fragile Foundations: A report on America's public works. Report to the President and the Congress.

Walski, T.M. and A. Pelliccia. 1982. Economic analysis of water main breaks. *Journal of the American Water Resources Association* March: 140-147.

Acknowledgement

Support for this study was provided, in part, by the National Science Foundation, Grant No. CES-8617984, titled, "Hierarchical-multiobjective management of large scale infrastructure," under the direction of Dr. Jack Scalzi of Structures, Geomechanics and Building Systems.

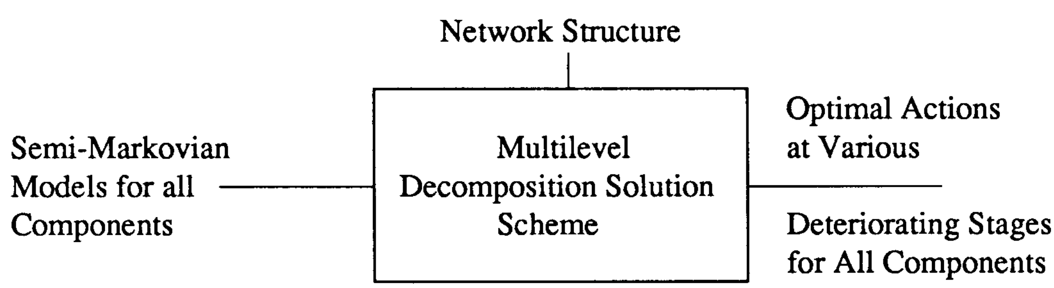

Figure 2. Input and Output of the Multilevel Decomposition Solution Scheme