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Preventive maintenance and replacement scheduling for repairable and maintainable systems using dynamic programming ☆

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ABSTRACT

This paper presents mathematical models and a solution approach to determine the optimal preventive maintenance schedules for a repairable and maintainable series system of components with an increasing rate of occurrence of failure (ROCOF). The maintenance planning horizon has been divided into discrete and equally-sized periods and in each period, three possible actions for each component (maintain it, replace it, or do nothing) have been considered. The optimal decisions for each component in each period are investigated such that the objectives and the requirements of the system can be achieved. In particular, the cases of minimizing total cost subject to a constraint on system reliability, and maximizing system reliability subject to a budgetary constraint on overall cost have been modeled. As the optimization methodology, dynamic programming combined with branch-and-bound method is utilized and the effectiveness of the approach is presented through the use of a numerical example. Such a modeling approach should be useful for maintenance planners and engineers tasked with the problem of developing recommended maintenance plans for complex systems of components.

1. Introduction

Preventive maintenance is a broad term that includes a set of activities to improve the overall reliability and availability of a system. All types of systems, from conveyors to cars to overhead cranes, have prescribed maintenance schedules set forth by the manufacturer that aim to reduce the risk of system failure and total cost of maintaining the system. Preventive maintenance activities generally consist of inspection, cleaning, lubrication, adjustment, alignment, and/or replacement of sub-systems and sub-components that wear-out. Regardless of the specific system in question, preventive maintenance activities can be categorized in one of two ways, component maintenance or component replacement. An example of component maintenance would be maintaining proper air pressure in the tires of an automobile. Note that this activity changes the aging characteristics of the tires and, if done correctly, ultimately decreases their rate of occurrence of failure in the tires. An example of component replacement would be simply replacing one or more of the tires with new ones. Obviously, preventive maintenance involves a basic trade-off between the costs of conducting maintenance and replacement activities and the cost savings achieved by reducing the overall rate of occurrence of system failures. Designers of preventive maintenance schedules must weigh these individual costs in an attempt to minimize the overall cost of system operation. They may also be interested in maximizing the system reliability, subject to some sort of budgetary constraint.

This paper presents mathematical models for planning preventive maintenance and replacement activities for a repairable and maintainable system with multiple components, each of which is subject to an increasing rate of occurrence of failure (ROCOF), also known as "deterioration", over a discrete number of periods. In each period (which could be defined as an hour, a day, a week, a month, etc.) it is assumed that one of three distinct actions can be planned for each component in the system:

(a) *Do nothing* – In this case, no action is to be taken on the component. This is often referred to as leaving a component in a state of "bad-as-old", where the component of interest continues to age normally.
(b) *Maintenance* – In this case the component is maintained, which places it into a state somewhere between "good-as-new" and "bad-as-old". In this paper, the maintenance action reduces the effective age of the component by a stated percentage of its actual age. Because components subject to wear out experience an increasing ROCOF, this reduction in effective age results in a reduction in ROCOF as well.
(c) *Replacement* – In this case, the component is to be replaced, immediately placing it in a state of "good-as-new", *i.e.*., its age is effectively returned to time zero.

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The problem then becomes one of designing a sequence of actions (a), (b) or (c) for each component in the system for each period over the planning horizon such that overall costs are minimized or the reliability of the system is maximized. The motivation of this research comes from the complexity of finding optimal preventive maintenance policies in multi-component systems and the equipment replacement problem that have been separately studied so far. This research integrates the preventive maintenance optimization in the optimal reliability design area with the component replacement problem and employs a combination of dynamic programming and branch-and-bound method to find the global optimum solution. The organization of the paper is as follows:

In Section 2, a brief review of existing literature in the various types of models and algorithms in preventive maintenance optimization and equipment replacement problem is presented and the contribution of the research is clarified. Section 3 presents the configuration of the system and formulation procedure of the optimization models. Section 4 provides the proposed optimization models and Section 5 presents a dynamic programming formulation of the optimization models and discuses the solution methodology to solve the proposed models. In Section 6, the developed models are applied to find the best preventive maintenance and replacement decisions of a numerical example to prove the effectiveness of the proposed model and the solution approach. Finally, Section 7 provides a conclusion of the research with summary and remarks.

2. Literature review

2.1. Preventive maintenance optimization

Optimization model is a mathematical model that refers to choosing the best solution from all feasible solutions. Optimization models have been widely developed and used to find optimal preventive maintenance schedules for a variety of systems. Here we review the most recent ones and those that are particularly related to our modeling and solution approach. Yao, Fu, Marcus, and Fernandez-Gaucherand (2001) present a two-layer hierarchical model that optimizes the preventive maintenance scheduling in semiconductor manufacturing operations. They develop a Markov decision process and optimize this model via a mixed-integer linear programming model. They define profit of cluster tools production as the objective function to be maximized and consider time window for preventive maintenance activities and limitation of resources as the constraint, which were non-linear functions. In order to achieve a global optimum, they transfer the non-linear functions into linear ones and use EasyModeler and OSL as the optimization software. Later Yao, Fernandez-Gaucherand, Fu, and Marcus (2004) extend their previous model to be more general, apply this extended model in a production line of a semiconductor manufacturing system, and show the application of it via numerical examples. Jayakumar and Asagarpoor (2004) present a linear programming model in order to optimize the maintenance policy for a component with deterioration and random failure rate. They determine optimal mean times of minor and major preventive maintenance actions based on maximizing the availability of the component by formulating and solving a linear programming model of Markov decision process. Robelin and Madanat (2006) develop a maintenance optimization model for bridge decks via Markov chain process. In this paper, they classify optimization models into two categories. The optimization models with physically based deterioration models have limited number of decision variables and the optimization models with simpler deterioration models have more and sophisticated decision variables. They apply Markov chain methodology with states based on history of deterioration and maintenance actions and utilize dynamic programming as the solution approach to solve Markov decision process. Canto (2006) presents an optimization model to schedule a preventive maintenance of a power plant. He considers total cost of various operations as the objective function and uses the Bender's decomposition method to solve a mixed-integer linear programming model.

Budai, Huisman, and Dekker (2006) present two mixed-integer linear programming models for preventive maintenance scheduling problems. The authors assume the total cost including possession costs, maintenance costs, and the penalty costs of early consecutive maintenance activities as the objective function for both models. They present and prove a theorem about the NP-hard structure of the preventive maintenance scheduling problem. In addition, they develop four heuristic optimization algorithms, two for each model, and compare the computational results obtained from exact algorithms with the results achieved from heuristic algorithms and mention the advantages of each solution methodology. Another excellent study in this area is by Tam, Chan, and Price (2006), who develop three non-linear optimization models: one that minimizes total cost subject to satisfying a required reliability, one that maximizes reliability at a given budget, and one that minimizes the expected total cost including expected breakdown outages cost and maintenance cost. They utilize MS-Excel Solver as the optimization software that uses a generalized reduced gradient (GRG) algorithm to solve the non-linear optimization models. Using these models, they determine the optimal maintenance intervals for a multi-component system but their models consider only maintenance actions for components and do not consider replacement actions. Kuo and Chang (2007) develop an integrated maintenance scheduling and production planning optimization model for a single machine based on preventive maintenance strategies on production schedules in order to minimize total tardiness. They find that the optimal maintenance policy is a constraint on the production schedule when machine shuts down due to cumulative damage failure process. The computational results achieved by dynamic programming show that by increasing the number of jobs the effect of jobs due dates on the optimal maintenance policy is decreased.

Preventive maintenance scheduling has been proved as an NP-hard combinatorial optimization problem in many situations and systems. Because of complexity of the optimization models developed for preventive maintenance problem, metaheuristic algorithms and in particular genetic algorithms have been widely used in several research papers as a major optimization approach. Usher, Kamal, and Hashmi (1998) present an optimization maintenance and replacement model for a single-component system. They determine an optimal preventive maintenance schedule for a new system subject to deterioration, by considering the time value of money in all future costs, increasing rate of occurrence of failure over time and the use of the improvement factor to provide for the case of imperfect maintenance actions. In addition, they provide a comparison of computational results among random search, genetic algorithm, and branch and bound algorithms. Levitin and Lisnianski (2000) present a research in which an optimization model was developed in order to determine the optimal replacement scheduling in multi-state series–parallel systems. They consider an increasing failure rate based on the expected number of failures during time intervals and define summation of maintenance activities cost along with cost of unsupplied demand due to failures of components as the objective function. Finally, they utilize universal generating function approach and applied genetic algorithm to find the optimal maintenance policy. Cassady and Kutanoglu (2005) develop and present an integrated