Computers & Industrial Engineering 61 (2011) 64–75

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Sensitivity analysis and comparison of algorithms in preventive maintenance and replacement scheduling optimization models ☆

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ARTICLE INFO

Article history:
Received 7 June 2009
Received in revised form 25 July 2010
Accepted 18 February 2011
Available online 27 February 2011

Keywords:
Preventive maintenance and replacement scheduling
Optimization models
Multi-component systems
Sensitivity analysis
Comparison of algorithms

ABSTRACT

In this research, new optimization models are developed to determine the optimal preventive maintenance and replacement schedules in repairable and maintainable systems. The objective is to determine a plan of actions for each component in the system while minimizing the total cost and maximizing overall system reliability over the planning horizon. Experimental results of a sensitivity analysis on the optimization models are presented and evaluated. These experiments investigate the effect of the parameters on the structure of optimal preventive maintenance and replacement schedules in multi-component systems. Two factorial design experiments based on the cost associated with maintenance and replacement activities and reliability characteristic parameters are constructed and analyzed. In addition, a comprehensive experiment is designed to analyze and compare the efficiency and accuracy of the exact and metaheuristic algorithms.

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1. Introduction

Preventive maintenance is defined as a set of activities aimed at improving 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. Preventive maintenance activities generally consist of inspection, cleaning, lubrication, adjustment, alignment, and/or replacement of sub-components that wear-out. In general, preventive maintenance activities can be categorized in one of two ways, component maintenance or component replacement. It is clear that 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 prioritize these individual costs to minimize the overall cost of system operation. They may also be interested in maximizing the system reliability, subject to some sort of budget constraint.

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 and replacement schedules for a variety of systems. Analytical methods find optimum solutions of mathematical models using derivatives for uncontained problems. Optimum solutions of constrained problems are instead found by the Lagrange multiplier method. This method calculates a system of inequalities called the Karush–Kuhn–Tucker conditions, which may then be used to calculate the optimum. Canfield (1986) assumes an increasing failure rate based on the Weibull distribution function and determines optimal cost of maintenance policies by defining the average cost-rate of system operation and applying an analytical method as the solution approach. Westman and Hanson (2000) develop a mathematical model to determine the mean time to failure (MTTF) as a function of uptime for a workstation in a multi-stage manufacturing system. They mention that this methodology captures the flexibility and multi-stage properties of manufacturing systems and can generate preventive maintenance policies. Panagiotidou and Tagaras (2007) develop an optimization model to find the best preventive maintenance schedules in a manufacturing process. The researchers combine age-based and condition-based approaches into the optimization

☆ This manuscript was handled by area editor E.A. Elsayed.

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0360-8352/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cie.2011.02.012

model with the minimization of total cost and solve it by applying Karush–Kuhn–Tucker (KKT) conditions of optimality.

Exact algorithms reach exact optimal solutions of mathematical models, while approximation algorithms seek an approximation that is close to the true optimal solutions. 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. 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. Canto (2006) presents an optimization model to schedule a preventive maintenance of a real power plant over a planning horizon. He considers the total cost of various operations as the objective function and uses Bender's decomposition 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. They present and prove a theorem about the NP-hard structure of the preventive maintenance scheduling problem and use CPLEX to implement the optimization models for a case study of railway maintenance scheduling. The authors also develop four heuristic optimization algorithms, two for each model, and compare the computational results obtained from exact algorithms in CPLEX with the results achieved from heuristic algorithms and mention the advantages of each solution methodology. Another study in this area is presented by Tam, Chan, and Price (2006), who develop three nonlinear 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 nonlinear optimization models. Alardhi, Hannam, and Labib (2007) present a binary integer linear programming model in order to find the best preventive maintenance schedule in separated and linked cogeneration plants. The researchers define the availability of the power and desalting equipment as the objective function to be maximized and perform a sensitivity analysis on the model to assess the robustness and analyze the sensitivity of the parameters.

Heuristic and metaheuristic algorithms designate a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. Metaheuristics make few or no assumptions about the problem being optimized and can search very large spaces of candidate solutions. However, metaheuristics do not guarantee an optimal solution is ever found. Because of complexity of the optimization models developed for preventive maintenance problem, metaheuristic algorithms and in particular genetic algorithms have been used in several research papers as a major optimization approach. Kim, Nara, and Gen (1994) combine genetic algorithms with simulated annealing in order to optimize a large-scale and long-term preventive maintenance and replacement scheduling problem. By using this approach, they achieve a near optimal solution in a short period of time compare to the computational time of a simple genetic algorithm. 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 an improvement factor to provide for the case of imperfect maintenance actions. They also provide a comparison of computational results among random search, genetic algorithm, and branch and bound algorithms. Levitin and Lisnianski (2000a) define a multi-state system in which all or some of the components have different performance levels. Their optimization model is based on minimization of cost subject to a required level of reliability. They apply a universal generating function technique and use a genetic algorithm to determine the best maintenance strategy. Levitin and Lisnianski (2000b) present additional research in which an optimization model is developed in order to find optimal replacement schedule in multi-state series–parallel systems. They consider an increasing failure rate based on the expected number of failures during time intervals and define the summation of maintenance activities cost along with cost of unsupplied demand due to failures of components in the objective function. The researchers utilize a universal generating function approach and apply a genetic algorithm to find the optimal maintenance policy. Wang and Handschin (2000) develop a new genetic algorithm by modifying the basic operators, crossover and mutation, of a standard genetic algorithm to improve the computational complexity of their genetic algorithm to achieve faster convergence and to prevent production of infeasible solutions. Allaoui and Artiba (2004) present a combination of simulation and optimization models in order to solve the NP-hard hybrid flow shop scheduling problem with maintenance constraints and multiple objective functions. They prove that the effectiveness of the simulated annealing algorithm is better than other heuristic algorithms under the same conditions. Limbourg and Kochs (2006) propose several techniques to represent the decision variables in preventive maintenance scheduling models that use heuristics and metaheuristics optimization algorithms. They test various non-standard approaches and compare them to binary representations by a heuristic algorithm and the computational results show that effectiveness of their approach in terms of computational time and accuracy. Suresh and Kumarappan (2006) develop an optimization model and use a genetic algorithm combined with simulated annealing. It is mentioned that the method could produce better solutions if some changes and modification are made into the solution procedure.

These studies are of interest and could be applied to a wide variety of applications but the effect of components specifications on the structure of optimal schedule and comparison of different types of algorithms have not been studied yet. This paper defines a general configuration for multi-component systems and then develops mathematical formulations to determine optimal preventive maintenance and replacement schedules. The main contribution of this research is to present experimental results of a sensitivity analysis on preventive maintenance and replacement scheduling optimization models. These experiments investigate the effect of the parameters on the structure of optimal schedules in multi-component systems. Two factorial design experiments based on the cost associated with maintenance and replacement activities and reliability characteristic parameters are constructed and analyzed. In addition, a comprehensive experiment is designed to analyze and compare the efficiency and accuracy of the exact and heuristic algorithms and the advantages of each are shown. The organization of the paper is as follows. In Section 2, configuration of the system is illustrated and in Section 3 two optimization models to minimize the total cost and maximize the overall reliability of series system of components are presented. Section 4 demonstrates the structure of the experimental design of sensitivity analysis and shows the computational results of different scenarios. Section 5 compares the computational accuracy and efficiency of exact and metaheuristic algorithms in both optimization models and finally, Section 6 concludes the research with summary and remarks.

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