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Multi-objective preventive maintenance and replacement scheduling in a manufacturing system using goal programming

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ABSTRACT

This research presents a new multi-objective nonlinear mixed-integer optimization model to determine Pareto-optimal preventive maintenance and replacement schedules for a repairable multi-workstation manufacturing system with increasing rate of occurrence of failure. The operational planning horizon is segmented into discrete and equally-sized periods and in each period three possible maintenance actions (repair, replacement, or do nothing) have been considered for each workstation. The optimal maintenance decisions for each workstation in each period are investigated such that the objectives and the requirements of the system can be achieved. Total operational costs, overall reliability and the system availability are incorporated as the objective functions and the multi-objective model is solved using a hybrid Monte Carlo simulation and goal programming procedure to obtain set of non-dominated schedules. The effectiveness and feasibility of the proposed solution methodology are demonstrated in a manufacturing setting and the computational performance of method in obtaining Pareto-optimal solutions is evaluated. Such a modeling approach and the proposed solution algorithm could be useful for maintenance planners and engineers tasked with the problem of developing optimal maintenance plans for complex productions systems.

1. Introduction

Production scheduling and preventive maintenance planning are among the most common and significant problems faced in manufacturing industries in which workstations (i.e., machines, industrial robots, etc.) are considered as the main resources to carry out the production plan. The production plan and maintenance actions directly affect the workstations' operation schedules. Production planning is concerned with allocating limited resources to a set of jobs along with certain objective functions that should to be optimized, i.e., in order to meet the deadlines by minimizing the sum of tardiness or makespan. According to the configuration of the workshop (single workstation, multiple workstations, flow shop, job shop, open shop and hybrid systems), some critical objectives should be optimized and certain types of constraints must be taken into account (preemption, setups, etc.). In real manufacturing systems, workstations may be subject to some unavailability periods due to unexpected failures or just because of performing scheduled maintenance activities. In maintenance scheduling, the most important task is to establish an appropriate preventive maintenance plan which optimizes certain objective functions, like minimizing maintenance costs or keeping the workstations in a good condition all the time. However, most of the studies in maintenance optimization do not take into account the production requirements encountered in practice. Considering inherent interdependent relationship between the manufacturing operations and the maintenance scheduling, the two activities are generally planned and executed separately in real systems. The relationship between production and maintenance has been literally considered as a conflict in optimal decisions. These conflicts may result in an unsatisfied demand in production due to the interruptions resulting from the preventive maintenance interventions or workstation failures.

In this research, we develop a multi-objective model by taking into account the workstations reliability for preventive maintenance aspect, the overall availability of the system for production purposes, and total operational costs for both preventive maintenance and production planning decisions. This modeling approach allows the decision maker to achieve compromise solutions meeting at best for three important criteria by which the Pareto-optimal solutions (also known as the efficient frontier) are determined. The rest of this paper is organized as follows. Section 2 reviews the existing literature of the problem of interest. Section 3 formulates the problem containing possible preventive maintenance actions, objective functions and necessary mathematical equations. The hybrid solution method is presented in Section 4 and Section 5 presents the computational results in a manufacturing application.

2. Literature review

The effectiveness of the preventive maintenance scheduling under different conditions such as shop load, job sequencing rule, maintenance capacity and strategy was studied in several earlier

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studies (Banerjee and Burton, 1990; Burton et al., 1989; Mosley et al., 1998). These studies tested the effectiveness of simple preventive maintenance policies using discrete-event simulation, rather than optimizing them along with production scheduling decisions. There are also other research that extend the simple machine scheduling models by considering the maintenance decisions or constraints (Mannur and Addagatla, 1993). A multi-criteria approach to find optimal preventive maintenance intervals of components in a paper factory production line with total expected costs and reliability as the objective functions was proposed by Chareonsuk et al. (1997). Gharbi and Kenne´ (2005) could find an approximation for optimal control policies and values of input factors by combining analytical formulation with simulation-based statistical tools such as experimental design and response surface methodology in a production and preventive maintenance planning problem. A comprehensive research in the area of integrating preventive maintenance scheduling and production planning was found in Ruiz et al. (2007). In this study, three different policies for preventive maintenance schedules and the total manufacturing time were defined for flow shop problems. The authors applied six different adaptations of heuristic and metaheuristic algorithms to evaluate the policies over two sets of problems and concluded that ant colony optimization and genetic algorithms solve these types of problems effectively overcoming other types of metaheuristics.

Integrated preventive maintenance and job shop scheduling problem for a single-machine was tackled in Cassady and Kutanoglu (2003, 2005), Sortrakul et al. (2005), Leng et al. (2006), Batun and Azizoglu (2009) and Pan et al. (2010). In these studies, minimization of total weighted expected completion time is considered as the objective function. As a comparison, the obtained computational results of integrated model were compared with the results achieved from solving preventive maintenance scheduling and job scheduling problems independently. Furthermore, Sortrakul and Cassady (2007) tried to improve the solution procedures by solving a larger version of the integrated preventive maintenance and production scheduling model using genetic algorithms. Allaoui and Artiba (2004) proposed an integrated simulation and optimization method to solve a hybrid flowshop problem under maintenance constraints to optimize several objectives while considering flow time and jobs due dates along with setup, cleaning, and transportation times. Allaoui and Artiba (2006) also explored the non-preemptive two-stage flexible flowshop scheduling with a single machine on the first stage and multiple machines on the second stage under minimization of the makespan. The researchers also presented the complexity analysis of simultaneously scheduling multiple jobs and preventive maintenance scheduling on a two-machine flow shop setting to minimize the makespan (Allaoui et al., 2008). Jin et al. (2009) presented a single-machine integrated job shop and preventive maintenance scheduling model in order to find an optimal sequence of jobs along with an optimal maintenance plans to minimize the total weighted expected completion time of the jobs.

The theoretical aspects of optimal integrated production and preventive maintenance plans has been investigated for a single machine under a cumulative damage process with the goal of minimizing total tardiness (Kuo and Chang, 2007). In another study, five objectives functions of maintenance cost, makespan, weighted completion time of jobs, total weighted tardiness, and machine availability were considered simultaneously in a multi-objective integrated production and maintenance planning problem solved by a multi-objective genetic algorithm (Yulan et al., 2008). Benbouzid-Sitayeb et al. (2008) employed an ant colony optimization approach to solve integrated production and preventive maintenance scheduling problem in permutation flowshops. The obtained results were also compared to those of an integrated genetic algorithms developed in previous works. Bi-objective integrated production and maintenance scheduling models have been presented to determine the Pareto-optimal front of the assignment of production tasks to machines along with preventive maintenance activities in a production system (Berrichi et al., 2009; Berrichi et al., 2010). These studies developed and tested series of genetic algorithms to solve the problem. Hua et al. (2010) developed an integrated optimization model and showed the advantage and practicality of the optimal integrated policy over independent optimal production and maintenance schedules driven by separate models. The study was further expanded by considering a flowshop with multiple machines connected in series, aiming to minimize the total weighed system cost (Miaoqun et al., 2010). In another research, a bi-objective optimization model integrating flexible job shop problem with preventive maintenance scheduling was developed to minimize the makespan and system unavailability (Moradi et al., 2011). Integrating flexible flowshops and periodic preventive maintenance policies to minimize makespan of workstations using genetic algorithm and simulated annealing were presented in Naderi et al. (2009, 2011).

This research tries to incorporate preventive maintenance activities introduced in Berrichi et al. (2009, 2010), Moghaddam and Usher (2011) and develops a multi-objective preventive maintenance and replacement scheduling model aimed at finding Pareto-optimal schedules for multi-workstation manufacturing systems. It is found that none of the reviewed research studies considered the simultaneous combination of total operational costs, system reliability and overall availability of the production system in their modeling approach. In addition, most of these efforts try to model single-component or single-machine production systems which are very uncommon in real and large-scale applications. Hence the first contribution of this research is to develop a comprehensive mathematical model to be able to capture broader aspects of the production and maintenance scheduling problems in multi-component manufacturing systems without any predefined user preferences for different criteria of the system. On the other hand most of the above reviewed literature employed or developed some sort of heuristic algorithms to solve their proposed models. These algorithms are best known to their capability of obtaining good or near optimal solutions. However attainment of the exact optimal solution(s) is never guaranteed. Therefore, the second contribution of our study is to develop and test a novel solution procedure to achieve exact Prato-optimal solutions using combination of simulation and optimization methods. Computational results confirm that there are indeed trade-offs among the objectives of total operational costs, system reliability and availability. Capturing these trade-offs provides invaluable information to improve systems performance over the range of designated goals.

3. Problem formulation

Parameters

N : number of workstations
L : length of the planning horizon
T : number of time intervals over the planning horizon
K : number of objective functions
λ_i : scale parameter (characteristic life) of workstation i
β_i : shape parameter of workstation i
α_i : improvement factor of maintenance action on workstation i
F_i : unexpected failure cost of workstation i
M_i : maintenance (including inspection and repair) cost of workstation i
R_i : replacement cost of workstation i
TPM_i : time to perform preventive maintenance on workstation i