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Single-machine-based joint optimization of predictive maintenance planning and production scheduling

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ABSTRACT

Maintenance planning and production scheduling are two activities that are inter-dependent but most often performed independently in manufacturing. The maintenance planning affects both available production time and failure probability. However, in previous research, the maintenance planning only considers preventive maintenance and may result in maintenance shortage or overage. And the deterioration and health status of machines from prognostics are often ignored. The paper presents an integrated decision model that coordinates predictive maintenance decisions based on prognostics information with a single-machine scheduling decisions so that the total expected cost is minimized. In the integrated model, the health status and dummy age subjected to machine degradation is considered. Finally, a case study is used to demonstrate the value of the proposed methods. And the performance of the integrated solution is compared with solutions obtained from solving the predictive maintenance planning and production scheduling problems independently. The results prove its efficiency.

1. Introduction

Production scheduling and maintenance planning are among the most common and significant problems faced by the manufacturing industries [1]. Production scheduling problems generally involve the assignment of jobs or operations to machines, while maintenance actions are carried out to retain a system or to restore it to an acceptable operating condition. Despite the trade-offs between the two activities, they are typically planned and executed independently in real manufacturing settings even if manufacturing productivity can be improved by optimizing both production scheduling and maintenance planning decisions simultaneously.

Maintenance activities take time that could otherwise be used for production, but delaying maintenance for production may increase the probability of machine failure. Hence, there are trade-offs and conflicts between maintenance planning and production scheduling. Generally, maintenance can be classified into corrective maintenance (CM) and preventive maintenance (PM). The corrective maintenance involves the repair or replacement of components which have failed or broken down [2]. The preventive maintenance is a schedule of planned maintenance actions aimed at the prevention of system breakdowns and failures [3]. Recently, predictive maintenance becomes more desirable in many application domains where safety, reliability and availability of systems are considered critically, and it can also increase productivity, efficiency and availability of systems [4]. Our contention is that manufacturing system productivity could be improved by integrating these decisions. We investigate this contention using an integrated predictive maintenance planning and production scheduling model.

One machine may fail due to its degradation and usage. The consequent repair and replacement will make machine unavailable, which disorders production scheduling. Hence, how to schedule maintenance planning to keep machines in good operation condition and high reliability, and further make production scheduling based on machine maintenance has become a vital issue for the achievement of intelligent manufacturing [5–8].

As the importance of joint optimization of maintenance and production scheduling has been highlighted or explained, this topic has attracted significant research interest for several decades. As the basic foundation for studying more complex systems [9,10], the joint optimization of a single machine has been extensively researched. Graves and Lee [11] considered a single-machine scheduling problem with total weighted completion time as the objective function just as we did, but they scheduled only one maintenance activity during the planning horizon. They showed some complex results depending on the length of the planning horizon. Qi et al. [12] considered a similar single-machine

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problem with possibly multiple maintenance actions, but they do not explicitly model the risk of not performing maintenance, which is explicitly captured in our analysis. Lee and Chen [13] extended this to parallel machines, but still with only one maintenance action. Pan et al. [14] researched the optimization problem considering a single machine system under a perfect PM policy. Fitouhi and Nourelfath [15] dealt with the problem of integrating non-cyclical PM and tactical production planning for a single machine. They also integrated the noncyclical preventive maintenance with tactical production planning in multi-state systems [16]. Pan et al. [17] proposed a scheduling model for single machine system incorporating production scheduling and machine maintenance, so as to maximize machine's availability. Wang and Liu [18] used a branch-and-bound algorithm to optimize the joint problem of PM planning and production scheduling. Wong et al. [19] proposed a method for joint production scheduling problem by considering multi-resources and preventive maintenance, and proved its validity. Wang and Liu [20] dealt with an integrated optimization model for production scheduling and PM in a single machine with its time to failure subject to a Weibull probability distribution. Chen et al. [21] connected production scheduling with maintenance planning for a repairable system. Cui et al. [22] used genetic algorithm to solve the joint problem for a single machine, and joint decision-making policy could obtain better result than independent policy. Mirabedini and Iranmanesh [23] integrated flow shop scheduling problem with preventive maintenance activities in order to minimize the total completion time, and proposed two meta-heuristics based on simulated annealing and genetic algorithm. Liu et al. [24] integrated production, inventory and preventive maintenance models for a multi-product production system. Chen et al. [25] integrated the production scheduling with maintenance planning for a repairable system. Three types of maintenance were performed to restore the machines. Lu et al. [26] also proposed a joint model for integrating run-based PM into the production scheduling problem. Xiao et al. [1] proposed a joint optimization model to minimize the total cost including production cost, preventive maintenance cost, minimal repair cost for unexpected failures and tardiness cost. However, for maintenance, prognostics and diagnostics information are not considered. That is, the decisions are based on the reliability information obtained from similar systems while the prognostics and diagnostics information are not considered. In this paper, the predictive maintenance planning will consider the diagnostics information and prognostics information (or system degradation information).

The study of maintenance can also concern resource management, maintenance strategy optimization and evaluation. Recently, mathematical models have been established to describe predictive maintenance with consideration of spare parts inventory [27,28]. For example, Basten et al. [29] designed an optimal solution algorithm for joint problem of LORA (level of repair analysis) and spare parts stocking. Wang [30] presented a joint optimization method for both spare parts inventory control and preventive maintenance inspection interval. All these studies entail the joint optimization of maintenance and spare parts inventory. Thus, in current literatures, the maintenance mainly focused on the optimization of spare parts inventory and maintenance strategies is developed only with consideration of system states. In this paper, the maintenance focuses on the optimization of spare parts, maintenance personnel and tools. The paper proposes a multi-phase maintenance scheduling model using degradation information with consideration of resources planning.

These studies are of interest and could be applied in a wide variety of industries such as semiconductor manufacturing, transportation, and power generation. This paper provides a new method that incorporates prognostics information with available resources to obtain the optimal production scheduling and maintenance decisions. The contributions of the paper can be summarized as follows. First, system degradation information such as deterioration and aging is included to the proposed predictive maintenance model. Then, different maintenance actions could be developed for each failure state, and each system state will be optimized to a different target. Finally, an integrated decision model for both predictive maintenance and production scheduling is presented. The benefits of integrating the two activities into a decision-making process are described. Through a simple example, we demonstrate a procedure for identifying optimal scheduling, and maintenance decisions. We then provide insights gained from studying the model using numeric examples.

This paper is structured as follows. Section 1 gives the literature review about previous research. Section 2 introduces the production scheduling model. The predictive maintenance model is given in Section 3. Then, Section 4 presents a joint model for integrating predictive maintenance planning with production scheduling. An experiment is given in Section 5, a summary and some remarks conclude the paper in Section 6.

Table 1
Parameters description.

Parameters	Description
p_l	Processing time of job l
w_l	Weight of job l
d_l	Due date of job l
$p_{[g]}$	Processing time of gth job processed in the sequence
$w_{[g]}$	Weight of gth job processed in the sequence
$d_{[g]}$	Due date of gth job processed in the sequence
$o_{[g]}$	Completion time of gth job processed in the sequence
$t_{d_{[g]}}$	Tardiness of gth job processed in the sequence
$c_{[g]}$	Penalty cost due to tardiness of gth job processed in the sequence
c_l	Tardiness cost per unit of job l
c_p	Production cost per unit of the machine
m	Number of jobs to be scheduled at time zero

2. The production scheduling model

2.1. Notations

The parameters description in the current paper is shown in Table 1.

2.2. The mathematical model

In a manufacturing system, a single machine is needed to process a set of m jobs, and suppose that preempting one job for another is not permitted. Each position in the scheduling sequence of a single machine can only receive one job, and each job can be assigned to one position in the scheduling sequence. The aim of production scheduling is to obtain an optimal sequence for m jobs. Let

$$x_{gl} = \begin{cases} 1 & \text{if the } g\text{th job performed is job } l \text{ in a sequence} \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

Suppose that our objective is to minimize the total production cost, including production cost and tardiness cost. And the possiblity of machine failure is ignored. Then

$$p_{[g]} = \sum_{l=1}^{m} p_l x_{gl} \tag{2}$$

$$w_{[g]} = \sum_{l=1}^{m} w_l x_{gl} \tag{3}$$

$$d_{[g]} = \sum_{l=1}^{m} d_l x_{gl} \tag{4}$$

$$c_{[g]} = \sum_{l=1}^{m} c_l x_{gl} \tag{5}$$

$$o_{[g]} = p_{[1]} + p_{[2]} + \cdots + p_{[g]} = \sum_{u=1}^{g} p_{[u]} \tag{6}$$