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Joint optimization of production scheduling and machine group preventive maintenance

Lei Xiao [a,b], Sanling Song [b], Xiaohui Chen [a], David W. Coit [b,*]

[a] The State Key Lab of Mechanical Transmission, Chongqing University, Chongqing 400030, China
[b] Department of Industrial and Systems Engineering, Rutgers University, NJ 08854, USA

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ABSTRACT

Joint optimization models were developed combining group preventive maintenance of a series system and production scheduling. In this paper, we propose a joint optimization model to minimize the total cost including production cost, preventive maintenance cost, minimal repair cost for unexpected failures and tardiness cost. The total cost depends on both the production process and the machine maintenance plan associated with reliability. For the problems addressed in this research, any machine unavailability leads to system downtime. Therefore, it is important to optimize the preventive maintenance of machines because their performance impacts the collective production processing associated with all machines. Too lengthy preventive maintenance intervals may be associated with low scheduled machine maintenance cost, but may incur expensive costs for unplanned failure due to low machine reliability. Alternatively, too frequent preventive maintenance activities may achieve the desired high reliability machines, but unacceptably high scheduled maintenance cost. Additionally, product scheduling plans affect tardiness and maintenance cost. Two results are obtained when solving the problem; the optimal group preventive maintenance interval for machines, and the assignment of each job, including the corresponding start time and completion time. To solve this non-deterministic polynomial-time problem, random keys genetic algorithms are used, and a numerical example is solved to illustrate the proposed model.

1. Introduction

In this paper, we study a series system of machines which are processing different types of jobs. Different production process schedules affect production time and costs, which are also influenced by machine reliability and maintenance. Machine maintenance frequency also influences production scheduling. Therefore, production scheduling and machine maintenance are interrelated decisions, and together they determine the total cost. This relationship and the practicality of the problem causes this problem to be challenging and interesting.

Preventive maintenance (PM) can be effective for maintaining machines at a high level of reliability [1]. However, implementing scheduled maintenance activities can also lead to machine unavailability while PM is being performed [2,3]. For some series production systems, such as certain types of automated flow processing lines, any machine unavailability can lead to the entire system being down or unavailable. Therefore, minimizing machine unavailability and maintaining the system at a high level of reliability is vital for production to run smoothly. If PM actions are undertaken individually to each machine in the production system, it may take longer collectively to perform individual PM actions than by group PM where all machines are maintained at the same time during the production horizon. Individual PM means that an individual machine is preventively maintained only if the specific machine PM interval is reached. For the scheduling problems addressed in this research, when PM is being conducted on one machine, the other machines are also not working, even though they are not being maintained at that time.

For the jobs which are processed on the system, there are due dates. If jobs are finished after the given due dates, tardiness is accrued and a penalty cost is charged. For the individual PM policy, there may be frequent downtimes, more tardiness and the associated tardiness cost accumulates. To decrease total PM time and frequency, we propose a group maintenance policy for machines and joint optimization of maintenance and production scheduling. Different from the existing research, an effective group maintenance policy is considered, and the maintenance interval is

* Corresponding author. Tel.: +1 848 445 2033; fax: +1 732 445 5467.
E-mail addresses: leixiao211@163.com (L. Xiao), sanling@scarletmail.rutgers.edu (S. Song), chenxiaohui@cqu.edu.cn (X. Chen), coit@rci.rutgers.edu (D.W. Coit).

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Notation Description

i	machine, $i=1,2,\ldots,N$, where N is the total number of machines
j	job, $j=1,2,\ldots,M$, where M is the total number of jobs
T	Preventive Maintenance (PM) interval
t	time
$C_{p,j}$	production cost of the j^{th} job
C_p	total production cost
$a_{i,k\text{-}1}$	age of machine i before the k^{th} processing
$E_{i,k}$	completion time of the k^{th} processing on Machine i
$S_{i,k}$	Start time of the k^{th} processing on Machine i
t_p	time for performing PM
$p_{i,j}$	processing time for the j^{th} job on Machine i
$T_{d,N,j}$	due date of the j^{th} job on Machine N
$L_{N,j}$	lateness of the j^{th} job on Machine N
$T_{N,j}$	tardiness of the j^{th} job on Machine N
C_t	total tardiness cost
$C_{t,k}$	tardiness cost of the k^{th} processing
$C_{m,i}$	PM cost of Machine i
L_i	total effective number of PM actions on Machine i
UP_i	number of inapplicable PM actions on Machine i
$UP_{i,k}$	number of inapplicable PM actions on Machine i just before the k^{th} processing counted from just before the $(k-1)^{th}$ processing
$h_i(t)$	hazard rate function of Machine i
$R_i(t)$	reliability at time t of Machine i
$\tau_{i,l}$	processing time on Machine i in the l^{th} PM interval
$C_{r,i}$	minimal repair cost of Machine i
C_m	total cost of maintenance

Decision variables

$x_{i,j,k}$	1, if the k^{th} processing on the i^{th} machine is the j^{th} job; 0, otherwise
$y_{i,k}$	1, if PM is performed on Machine i before the k^{th} processing; 0, otherwise.
$z_{i,k}$	1, if PM is performed on Machine i during the k^{th} processing; 0, otherwise.

determined based on minimizing the total cost including cost from machine maintenance and production.

As the importance of joint optimization of PM and production scheduling has been realized, this topic has attracted significant research interest for several decades. As the basic foundation for studying more complex systems [4,5], the joint optimization of a single machine has been extensively researched [6–9]. Wang and Liu [7] used a branch-and-bound algorithm to optimize the joint problem of PM planning and production scheduling. Pan et al. [8] researched the optimization problem considering a single machine system under a perfect PM policy. Fitouhi and Nourelfath [10] integrated noncyclical PM and production planning for a single machine. Liu et al. [11] integrated production, inventory and preventive maintenance models for a multi-product production system.

The joint optimization of PM and production scheduling in a multi-machine system is more complex than in a single-machine system. In a single-machine system, the start time to process the next job is only related to the completion time of the current job on this machine and the PM schedule. Alternatively, in a multi-machine system, the start time to process the next job is related to both the completion time of current job on this machine, the completion time of the next job on the prior machine and the PM schedule. The final delivery time is a result of the entire system performance rather than each single machine. Hence, the joint problem in a multi-machine system is more complicated and meaningful. Many joint optimization models are built for multi-machine systems. Fitouhi and Nourelfath [12] integrated noncyclical PM scheduling and production planning for multi-state multi-component systems. Berrichi et al. [13] used an Ant Colony Optimization approach to optimize production and maintenance scheduling in a parallel system. Moradi et. al. [14] integrated fixed time interval PM and production for scheduling in a flexible job-shop problem. Zhou et al. [15] developed a dynamic opportunistic PM model for a multi-component system considering changes in job shop schedule, in which whenever a job was completed, PM opportunities were exploited and PM performed for all the components in the system.

An important consideration for repairable systems is when to maintain machines. Many models suggest that PM should be undertaken when the machine reliability decreases below a certain value or after a given time interval. For example, Jin et al. [16] considered multiple objectives for a single-machine system, where the machine is maintained as long as its reliability achieves a certain value. Similarly, Chen et al. [9] considered an imperfect PM system, in which PM is undertaken when the machine reliability decreases below a preset value, and each PM interval is determined according to a reliability threshold. Ji et al. [17] used a fixed maintenance interval when minimizing makespan. In practice, many companies perform PM at a fixed interval, so it is an important research topic, although there are other methods to determine PM intervals. For example, a PM interval can be determined based on the maximum system availability [6,18,19], or based on minimizing system unavailability [20–23]. Wong et al. [24,25] determined a noncyclic method. If the current machine age plus the next operation time is larger than the maximum machine age, a maintenance task is conducted after the current job completion.

In our new model, we developed a joint optimization model connecting group PM with production scheduling applied to a series system where PM on any machine leads to unavailability of all machines. A perfect PM policy is assumed. Two results are obtained by solving this problem to minimize the total cost. The first is the appropriate assignment of jobs to the machines, and the second is the determination of group PM interval.

The rest of the paper is organized as follows. Section 2 formulates the joint optimization problem and presents the objective function. Section 3 describes the method to solve the problem. An example is given in Section 4. The paper is concluded in Section 5.

2. Problem formulation

We formulate and optimize a challenging scheduling problem with group PM policies. For some applications, other machines can still operate while PM is being performed on a specific machine, but there are also other applications where any machine unavailability can lead to the entire system being unavailable or down due to the nature of an inter-dependent series system, i.e., a flow processing line with inter-dependent processes. These applications are the focus of this paper. Machine downtime may result from unexpected failures or scheduled maintenance. It is important to minimize the unavailability and maintain the system at a high level of reliability.