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Single-machine scheduling problems simultaneously with deterioration and learning effects under deteriorating multi-maintenance activities consideration ☆

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ABSTRACT

Maintenance is important to manufacturing process as it helps improve the efficiency of production. Although different models of joint deterioration and learning effects have been studied extensively in various areas, it has rarely been studied in the context of scheduling with maintenance activities. This paper considers scheduling with jointly the deterioration and learning effects and multi-maintenance activities on a single-machine setting. We assume that the machine may have several maintenance activities to improve its production efficiency during the scheduling horizon, and the duration of each maintenance activity depends on the running time of the machine. The objectives are to determine the optimal maintenance frequencies, the optimal maintenance locations, and the optimal job schedule such that the makespan and the total completion time are minimized, respectively, when the upper bound of the maintenance frequencies on the machine is known in advance. We show that all the problems studied can be solved by polynomial time algorithms.

1. Introduction

There are many situations where the processing time of a job may be subject to change due to deterioration or learning phenomena. Many researchers have devoted to address the jobs deterioration or the learning effect in scheduling under different machine environments. For a complete list of studies, the jobs deterioration scheduling problems are discussed in a survey by Cheng, Ding, and Lin (2004) and a recent book by Gawiejnowicz (2008); while the learning effect scheduling problems are discussed in reviews by Bachman and Janiak (2004), Biskup (2008) and Janiak and Rudek (2009).

The phenomena of deterioration and learning occurring simultaneously can be found in many real-life situations (see, e.g., Wang, 2007). Scheduling problems with the jobs deterioration and the learning effect have been extensively studied in recent years. Lee (2004) was the pioneer to introduce the deterioration and learning effects simultaneously in scheduling problems. Since then, many researchers have devoted large amounts of effort to this relatively young but vivid area of scheduling research from a variety of perspectives. The reader can refer to recent papers by Wang (2007), Wang and Cheng (2007), Wang (2009a, 2009b), Sun (2009), Wang et al. (2009), Wang, Huang, Wang, Yin, and Wang (2009), Yang and Kuo (2010), Huang et al. (2010) and Huang, Wang, Wang, Gao, and Wang (2010).

On the other hand, machine maintenance is often undertaken in manufacturing system to prevent premature machine failures with a view to sustaining production efficiency. However, the maintenance activity disrupts machine availability for production because the machine during the maintenance activity is unavailable for processing jobs. Scheduling under such an environment is known as scheduling with availability constraints. The problem of joint scheduling and availability constraint has attracted the attention by many researchers. For details on this stream of research, the reader can refer to the comprehensive surveys by Schmidt (2000) and Ma, Chu, and Zuo (2010), among others.

In addition, there has been growing interest in the literature to study scheduling problems with the jobs deterioration and the maintenance activity in recent years. Several studies have investigated this subject under different machine environments, which include Wu and Lee (2003), Ji, He, and Cheng (2006), Lee and Wu (2008), Low, Hsu, and Su (2008), Lodree and Geiger (2010) and Gawiejnowicz and Kononov (2010).

Most above mentioned references, which investigated scheduling problems with jointly the jobs deterioration and the maintenance activity, assumed that at most one maintenance activity is undertaken on a machine throughout the scheduling horizon. Nevertheless, in a real manufacturing process, a machine may require multi-maintenance activities to improve its production efficiency. Therefore, a more realistic machine scheduling model should take multi-maintenance activities into consideration. However, very

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little study has been done on this topic. Gawiejnowicz (2007) considered two single-machine problems of scheduling a set of independent, non-preemptive and proportionally deteriorating jobs with constraints on availability of the machine or jobs. In both problems the criterion of schedule optimality is the maximum completion time. Yang and Yang (2010a) investigated single-machine scheduling with jobs deterioration and maintenance activities to minimize the total completion time. They show that the problem remains polynomially solvable if the upper bound on the maintenance frequency is given.

Furthermore, most research considered machine scheduling with the maintenance activity assumed that the maintenance duration is a constant no matter what the condition of the machine is. However, this assumption may be inappropriate in many practical manufacturing processes. The maintenance duration may depend on the running time of the machine, that is, the later maintenance activity is performed, the worse the machine conditions are, and a longer time is needed to perform the maintenance activity. This kind of maintenance activity can be considered as a deteriorating maintenance activity. Several recent papers have been conducted to address the deteriorating maintenance activity in scheduling problems (see Kubzin & Strusevich, 2005, 2006; Mosheiov & Sidney, 2010; Yang, Yang, & Cheng, 2010; Yang & Yang, 2010a, 2010b).

To the best of our knowledge, however, scheduling with simultaneous considerations of the deterioration and learning effects and multi-maintenance activities has never been studied. The motivation for this study stems from the steel rolling mills. Before the manufacturing process, the ingot needs to preheat to the required temperature. Thus, the longer the ingot waits for the processing on the rolling machine, the lower the temperature drops and the longer the processing time needs (see Buzacott & Callahan, 1971; Posner, 1973; Bachman & Janiak, 2000; Ng, Cheng, Bachman, & Janiak, 2002). Moreover, the processing is operated by a skilled worker. The worker learns how to produce more efficiently during the process. As a result, the jobs deterioration and the learning effect simultaneously exist in the steel rolling mills process. On the other hand, if the temperature of an ingot, while waiting in a buffer between the furnace and the rolling machine, drops below a critical temperature, the ingot needs to be reheated to bring it up to the temperature required for rolling. The reheating time of the ingot depends on its waiting time in the buffer and is thus schedule-dependent, i.e., it requires more time if it is delayed. The reheating process can be considered as a deteriorating maintenance activity. The similar phenomena can also be found in other metal forming processes. Consequently, in this paper we consider single-machine scheduling problems simultaneously with the deterioration and learning effects and deteriorating multi-maintenance activities. We assume that the machine may have multi-maintenance activities during the scheduling horizon. We aim to find jointly the optimal maintenance frequencies, the optimal maintenance locations, and the optimal job schedule to minimize the makespan and the total completion time, respectively. We will provide polynomial time algorithms for all the problems studied.

The remaining part of the paper is organized as follows. In Section 2, we formulate the problem. In Sections 3 and 4, we propose polynomial time algorithms for the makespan and the total completion time minimization problems, respectively. Finally, conclusions are given in Section 5.

2. Notation and problem formulation

In this section, the notation that is used throughout the paper will be described first, followed by the formulation of the problem.

n	the total number of jobs;
k_0	the upper bound of the maintenance frequency on the machine, $k_0 \leqslant n-1$;
k	the maintenance frequency on the machine, $k \leqslant k_0$;
G_i	the ith group of jobs, $i = 1,2,\ldots,k+1$;
m_i	the duration of each maintenance activity, $i = 1,2,\ldots,k$;
n_i	the number of jobs assigned to group $G_i,\ i=1,2,\ldots,k+1,\ \sum_{i=1}^{k+1} n_i = n$;
$J_{[r]}^{(i)}$	the job assigned to the rth position of group G_i, $i = 1,2,\ldots,k+1$ and $r = 1,2,\ldots,n_i$;
$p_{jr}^{(i)}$	the actual processing time of job J_j scheduled in the rth position of group G_i, $i = 1,2,\ldots,k+1$, j, $r = 1,2,\ldots,n_i$;
$P_{r[r]}^{(i)}$	the actual processing time of job J_r assigned to the rth position of group G_i, $i = 1,2,\ldots,k+1$ and $r = 1,2,\ldots,n_i$;
$P_{[r]}^{(i)}$	the normal processing time of a job assigned to the rth position of group G_i, $i = 1,2,\ldots,k+1$ and $r = 1,2,\ldots,n_i$;
$C_{[r]}^{(i)}$	the completion time of a job scheduled in the rth position of group G_i, $i = 1,2,\ldots,k+1$ and $r = 1,2,\ldots,n_i$;
t_i	the running time of the machine between the $(i-1)$th and ith maintenance activities, $i = 1,2,\ldots,k$;
a	the learning factor of jobs, $a \leqslant 0$;
λ	the common deterioration rate of jobs, $\lambda \geqslant 0$;
μ	the basic maintenance time, $\mu > 0$;
σ	the deteriorating maintenance factor, $\sigma \geqslant 0$.

There are n jobs $J = \{J_1, J_2, \ldots, J_n\}$ to be processed on a single-machine. All the jobs are simultaneously available at time zero and the job preemption is not allowed. The machine can handle at most one job at a time and cannot stand idle until the last job is finished. To counteract the effect of deterioration, the machine may require maintenance activities to improve its production efficiency. We denote by k_0 the upper bound of the maintenance frequencies on the machine, where $k_0 \leqslant n-1$. We assume that the upper bound of the maintenance frequencies on the machine is known in advance.

If the machine is subject to exactly k times of maintenance activity, then there are $k+1$ groups of jobs in the job sequence. Observe that $k \leqslant k_0 \leqslant n-1$. For given the maintenance frequencies k on the machine, we denote by $P(n, k+1) = (n_1, n_2, \ldots, n_{k+1})$ the allocation vector of number of jobs in each group, where $n_i \geqslant 1$ is the number of jobs in group G_i and $\sum_{i=1}^{k+1} n_i = n$. If job J_j is started at time t and scheduled in position r of group G_i, then its actual processing time $p_{jr}^{(i)}$ is given by

$$p_{jr}^{(i)} = (p_j + \lambda t) r^a, \quad i = 1,2,\ldots,k+1, \quad j, r = 1,2,\ldots,n_i. \tag{1}$$

In addition, we further assume that: (1) the maintenance activity can be performed immediately after the processing of any job is completed, (2) after the maintenance activity, the machine reverts to its initial condition, and the deterioration effect starts anew, (3) the duration of each maintenance activity is a linear function of the running time of the machine and is given by $m_i = \mu + \sigma t_i$.

We consider the scheduling of the makespan and the total completion time minimization problems. For a given schedule, we denote by C_j the completion time of job J_j. Then $C_{\max} = \max_{j=1,2,\ldots,n}\{C_j\}$ and TC represent the makespan and the total completion time, respectively. Since the objectives are to minimize the makespan and the total completion time, we have to determine jointly the optimal maintenance frequencies, the optimal maintenance locations, and the optimal job schedule such that the makespan and the total completion time are minimized, respectively. Following the three-field notation in Kuo and Yang (2008), our problems are, respectively, denoted as $1/p_{jr} = (p_j + \lambda t) r^a, M \leqslant k_0/C_{\max}$ and $1/p_{jr} = (p_j + \lambda t) r^a, M \leqslant k_0/TC$, where M in the second field represents the maintenance activity.