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Machine scheduling with deteriorating and resource-dependent maintenance activity

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ABSTRACT

In this paper we investigate scheduling problems with a deteriorating and resource-dependent maintenance activity on a single machine. The duration of the maintenance is assumed to be dependent both on its starting time and on the resource allocated to it. The objective is determining the job sequence, the position to perform a maintenance activity and the amount of additional resource allocated to it such that the total cost of related measure and resource is minimized. The considered measures are the makespan, flowtime, maximum tardiness and combination of earliness, tardiness and due-date. Analysis results show that all the considered problems are polynomially solvable.

1. Introduction

In the traditional scheduling theory most literature gives the assumption that machines are available for processing at all times. However, this assumption is not justified in real manufacturing settings if there is a preventive maintenance activity. One type of maintenance, named rate-modifying activity (denoted by *rm* in the context), was first introduced into the scheduling field by Lee and Leon (2001), motivated by a common problem found in electronic assembly lines. Machine's performance is directly affected by changing the productivity through a *rm* activity, i.e., job processing time vary depending on whether the job is processed before or after the rate modification. Since maintenance activity usually brings higher production efficiency, the jobs processed after the maintenance activity have shortened processing times, while the machine is turned off with the absence of production during the maintenance activity. Thus, the scheduler has to take into account the balance between the temporary machine shutdown, and the improvement in production efficiency.

Lee and Leon (2001) consider several single-machine scheduling problems with a *rm* activity to minimize the makespan, flowtime, weighted flowtime, and maximum lateness. They provide algorithms for the objective functions mentioned above. Since then, *rm* activity becomes a popular topic among scheduling researchers and most research consider joint *rm* activity and other settings, such as precedence constraints, due-date assignment, variable/controllable processing times, delivery times, and multi-machines. The reader is referred to Mosheiov and Sidney (2003, 2010), Mosheiov and Oron (2006), Gordon and Tarasevich (2009), Lodree Jr and Geiger (2010), Wang, Wang, and Liu (2011), Yin, Cheng, Xu, and Wu (2012), Yang, Cheng, and Yang (2014a). To the best of the authors' knowledge, all of the stream of papers above, excluding Mosheiov and Sidney (2010) and Wang et al. (2011), assume that the duration of maintenance activity is fixed. Following Kubzin and Strusevich (2006), Mosheiov and Sidney (2010) and Wang et al. (2011) consider a setting where the maintenance activity is *deteriorating*. So far as we know, the concept "deteriorating" is derived from the scheduling with deteriorating job which is independently initiated by Gupta and Gupta (1988) and Browne and Yechiali (1990). Since then, scheduling problem with deteriorating jobs have received considerable attention in the research community of scheduling. For literature about such a field, reader can refer to Alidaee and Womer (1999), Cheng and Ding (2001), Ng, Cheng, Bachman, and Janiak (2002), Cheng, Ding, Kovalyov, Bachman, and Janiak (2003), Cheng and Ding (2003), Cheng, Kang, and Ng (2007), Cheng, Wu, and Lee (2008), Sun (2009), Ng, Wang, Cheng, and Liu (2010), Sundararaghavan and Kunnathur (1994) and survey by Cheng, Ding, and Lin (2004). Informally, in scheduling with deterioration, it is assumed that the latter a job starts, the longer it takes to process. Similarly,

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the maintenance activity is deteriorating means that the latter the maintenance process, the worse the machine conditions become, so that the *rm* activity requires more time. This situation usually occurs when maintenance includes refueling, cleaning, or partial replacement of tools. For literature considering deteriorating maintenance in the scheduling community, we may refer to Xu, Yin, and Li (2010), Luo, Chen, and Zhang (2010), Yang, Yang, and Cheng (2010), Cheng, Yang, and Yang (2012), Xu, Wan, Liu, and Yang (2015) and Luo and Ji (2015), etc. According to observation, most of the literature above assume that the maintenance is deteriorating and its duration is a linear function of its starting time. Following these papers, in this article we will also consider the similar situation where the maintenance activity is linearly deteriorating.

On the other hand, in the real applications, besides the machines, additional resource, such as funds, manpower, facilities, and energy, can be used for processing a job. It means that jobs can often be finished in shorter (longer) durations by increasing (decreasing) the additional resources, that is, the processing time of a job is controllable with the change of resource amount. This kind of resource allocation and its influence on sequencing has been confirmed in project scheduling with the time–cost trade-off model and has been widely studied (refer to books, Lawler (1976) and Badiru (1996)). Vickson (1980a, 1980b) makes the seminal research of production sequencing problems with controllable processing times. Following the impetus of Viskon's papers, scheduling problems involving controllable job processing times have been extensively studied by researchers. For research results on scheduling models considering controllable processing times and their practical applications, the reader may refer to literature Biskup and Cheng (1999), Cheng and Janiak (1994), Cheng and Kovalyov (1995), Cheng, Oğuz, and Qi (1996), Cheng, Janiak, and Kovalyov (1998), Cheng and Ding (2001) and surveys Nowicki and Zdrzałka (1990), Chen, Potts, and Woeginger (1999) and Shabtay and Steiner (2007b). For more recent works, we can refer to Shabtay and Kaspi (2004), Kaspi and Shabtay (2006), Shabtay and Steiner (2007a), Shabtay and Steiner (2008), Yedidsion, Shabtay, Korach, and Kaspi (2009), Leyvand, Shabtay, Steiner, and Yedidsion (2010), Shabtay and Steiner (2011), Yin, Cheng, Wu, and Cheng (2013), Oron (2013), Mor and Mosheiov (2014), Yang, Lai, and Yang (2014b), and so on.

In practice, as the controllable processing times studied by the literature cited above, the time needed to perform machine maintenance activity is not only deteriorating but also controllable by resource allocation. The motivation of resource-dependent maintenance procession is of the same nature, that is, maintenance operation can be completed in a shorter or longer duration by increasing or decreasing the required resource. Maintenance management is very common in practical production and the following is an applied example. For the metal cutting machine after working for a period of time, in order to make the machine more efficient production and prolong life, it is important to provide a maintenance activity, which includes cleaning the chip, wiping the dust, adding oil roller and partly replacing tools, etc. The workload of maintenance consists of two parts, one part is some basic machine maintenance operation required some basic maintenance time, the other part is the improving of machine and environment conditions determined by the length of working time, which is deteriorating and means that the longer the machine working time, the more severe tool wear and more chip production, the longer time needs to spend. On the other hand, to reduce maintenance time, we can use more resource such as power, tools, and personnel, but resulting in additional cost. That is, the maintenance time is controllable by resource allocation. To the best of our knowledge, however, there is no work pay attention to the controllability of maintenance time. As a result, we consider the single machine scheduling problems with deteriorating and controllable rate-modifying activity in this paper.

The rest of this paper is organized as follows. We present and formulate the problem in the next section. Then, we consider the makespan, flowtime and maximum lateness problem in Sections 3–5, respectively. The due-date assignment problem is discussed in Section 6. Finally, we conclude the paper in the last section.

2. Problem formulation

Suppose that n different jobs $J_1, \ldots, J_n$ are available for processing on a single machine at time zero. The machine can process only one job at a time. The scheduler may choose to perform *rm* activity to improve the product rate and at most once is allowed at all time. No production is carried out during the maintenance. We assume that the normal processing time of job j is denoted by p_j if the job is processed prior to *rm* activity, and $\gamma_j p_j$ $(0 < \gamma_j \leq 1)$ if it is scheduled after the *rm* activity, $j = 1, \ldots, n$. γ_j is the *modifying rate* of job j. The completion time of job j is denoted by $C_j, j = 1, \ldots, n$. For a given job sequence, let $[j]$ denote the j-th position, then the processing time, completion time and modifying rate of the job in the j-th position are denoted by $p_{[j]}, C_{[j]}$ and $\gamma_{[j]}$, respectively.

We now formulate the maintenance activity duration considered in this paper which is deteriorating and resource-dependent. Let s_{rm} and t denote the starting time and the length of *rm* activity. We assume that the maintenance time deteriorates *linearly*. The amount of additional resource allocated to the *rm* activity denotes $u \in [0, u_{\max}]$, where the upper bound, $u_{\max}$, is the maximum extra resource level that can be used in processing *rm* activity. We define the maintenance time as

$$t(s_{rm}, u) = t_0 + \delta s_{rm} - \tau(u),$$

where t_0 and δ are positive constants and $\tau(u)$ is a general resource consumption function which represent the compression time in maintenance activity. Generally, $\tau(u)$ is a non-decreasing continuous function in resource allocation theory such that $\tau(0) = 0$ and $0 \leqslant \tau(u) \leqslant \tau(u_{\max}) \leqslant \bar{\tau} < t_0$, where $\bar{\tau}$ is the maximum possible compression time of the *rm* duration.

In addition, we assume that the compression cost resulting from the additional application of u units of resource to the *rm* activity is found by a given continuous increasing function $g(u)$, which satisfies: for any constant L, only one argument for the minimum of function $g(u) - L\tau(u)$, denoted by $arg\ \min\{g(u) - L\tau(u) | u \in [0, u_{max}]\}$, exists and can be found in a constant time. Obviously, we can set $g(0) = 0$. Our problem considered in this paper includes scheduling decisions on

(a) the job sequence σ,
(b) the *rm* activity: whether or where to perform the *rm* activity, and
(c) the amount of additional resource allocated to *rm* activity,

so as to minimize the total cost

$$K(\sigma, rm, u) = \alpha f(\sigma, t) + g(u),$$

where $f(\sigma, t)$ is a measure in classic machine scheduling, $\alpha > 0$ is the unit penalty for the related measure. In this paper, we address the following three classic regular measures: the makespan $C_{\max}$, flowtime $\sum C_j$ and maximum tardiness $T_{\max}$. Let the corresponding cost per unit of the makespan, flowtime, maximum tardiness be $\alpha_1, \alpha_2, \alpha_3$, respectively. In addition, we also consider the earliness, tardiness measures in due-date assignment problem. Let α_4, α_5 and α_6 denote the unit cost of earliness, tardiness and due-date, respectively. Using conventional three-field notation scheme