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Single-machine scheduling with past-sequence-dependent delivery times and release times

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ABSTRACT

This paper studies the problem of single-machine scheduling with past-sequence-dependent delivery times, which was introduced in Koulamas and Kyparisis (2010) [5]. We focus on the scenario with release times such that any job is available for processing on or after its specific release time. Both preemptive and non-preemptive models are considered, aiming at minimizing the total completion time. An optimal algorithm is presented for the preemptive model where any job may be preempted during processing on the machine and then resumed from where it was interrupted later on. For the non-preemptive model, we show that it is NP-hard and mainly develop an approximation algorithm.

1. Introduction

In most industries, the manufacturing environment has a great influence on the treatment of jobs. Recent empirical studies in some industries have demonstrated that the waiting time of a job before processing may have an adverse effect on the processing time of the job (refer to Browne and Yechiali [2]; Koulamas and Kyparisis [4]; Koulamas and Kyparisis [5]). In electronic manufacturing industry, for example, an electronic component may be exposed to an electromagnetic or radioactive field while waiting in the pre-processing area. After its processing on one machine but before delivery to the customer, the component is required to be "treated", e.g., in a chemical solution, to remove the exposure effect from the electromagnetic/radioactive field (refer to Koulamas and Kyparisis [5]).

In literature, there are three models considering the waiting time-induced adverse effect on the processing of a job. The first model with *deterioration effect* was introduced by Browne and Yechiali [2]. In this model any job is with a so-called *deteriorating processing time* such that the processing time of a job increases in its waiting time. In the second model originated from Koulamas and Kyparisis [4], each job is with a *psd* (*past-sequence-dependent*) *setup time*, which is used to remove the adverse effect prior to the processing of the job via a setup operation. The third model with *psd delivery times* was introduced by Koulamas and Kyparisis [5], in which the adverse effect of waiting does not impede the schedule of job processing on one machine and shall be removed immediately after the completion of processing. The time consumed to remove the adverse effect for each job is called the job's *psd* delivery time.

Different from the traditional assumption with a job-specific constant delivery time in scheduling literature [7], Koulamas and Kyparisis [5] assumed that the *psd* delivery time of a job is proportional to the job's waiting time, i.e., the start time of processing. They focused on the case with a single-machine, and proved that the problem $1|q_{psd}|C_{\max}$ can be solved in $O(n)$ time by simply arranging the longest job to the last. They also proved that the problems $1|q_{psd}|L_{\max}$, $1|q_{psd}|T_{\max}$ and $1|q_{psd}|\sum U_j$ are polynomially solvable since these problems can be reduced to the

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corresponding problems without *psd* delivery times by appropriate transformations.

In this paper we focus on single-machine scheduling under the third model with *psd* delivery times. Motivated by the phenomena in practice such that all the jobs are not ready for processing at the beginning and they arrive over time due to the limitation of supplying or storage ability, we introduce release times of jobs into the model. To the best of our knowledge, there are no results on single-machine scheduling with *psd* delivery times and release times in literature. The remaining of the paper is organized as follows. In Section 2, we formally describe the problem considered. Section 3 presents an optimal algorithm for the preemptive model of the problem, and Section 4 derives an approximation algorithm for the non-preemptive model. Finally the paper is concluded in Section 5.

2. Problem description and notations

There is a single machine to process a set of n jobs $J_1, J_2, \ldots, J_n$. Each job J_j ($1 \leqslant j \leqslant n$) is released and becomes available at time r_j. Denote by p_j the processing time of job J_j, i.e., the time for processing the job on the machine.

Given a job processing schedule, denote by S_j, C'_j the start time and end time of processing J_j on the machine, respectively. Notice that in the preemptive model, since J_j may be preempted and resumed for one or more times, S_j represents the first time to start processing the job on the machine. In the environment with *psd* (*past-sequence-dependent*) delivery times, the processing of J_j is followed immediately by its *psd* delivery treatment. Denote by q_j the *psd* delivery time of job J_j. Notice that the *psd* delivery treatment does not occupy the machine, and as mentioned before it has no influence on the schedule of job processing. We assume as in Koulamas and Kyparisis [5] that q_j is proportional to the job's start time S_j. More precisely, q_j is formulated as

$$q_j = \gamma S_j, \quad j = 1, \ldots, n, \tag{1}$$

where $\gamma \geqslant 0$ is a constant. Let C_j be the completion time of job J_j, i.e., the end time of the job's *psd* delivery treatment. Then $C_j = C'_j + q_j$. For non-preemptive model, we have $C'_j = S_j + p_j$, and then

$$\begin{aligned} C_j &= C'_j + q_j = S_j + p_j + q_j \\ &= (1+\gamma)S_j + p_j, \quad j = 1, \ldots, n. \end{aligned} \tag{2}$$

For preemptive model, since job J_j may be preempted during processing for one or more times, let S^l_j, p^l_j be the last time to start processing J_j and the length of time interval for its last continuous processing on the machine, respectively. That is $C'_j = S^l_j + p^l_j$. In this model,

$$\begin{aligned} C_j &= C'_j + q_j = S^l_j + p^l_j + q_j \\ &= S^l_j + p^l_j + \gamma S_j, \quad j = 1, \ldots, n. \end{aligned} \tag{3}$$

For both preemptive and non-preemptive models, the objective is to minimize the total completion time. Denote by q_{psd} and *prmp* the model with *psd* delivery times and preemptions, respectively. Using the method of three-field notation [3], we denote the preemptive and non-preemptive models by $1|r_j, prmp, q_{psd}|\sum C_j$ and $1|r_j, q_{psd}|\sum C_j$ respectively.

3. Preemptive model $1|r_j, prmp, q_{psd}|\sum C_j$

In this section we consider the preemptive model $1|r_j, prmp, q_{psd}|\sum C_j$. The following lemma shows that each job shall be started for processing at its release time in an optimal schedule.

Lemma 1. *In an optimal schedule of $1|r_j, prmp, q_{psd}|\sum C_j$, the first start time of processing for each job is exactly its release time, that is $S_j = r_j$ for $1 \leqslant j \leqslant n$.*

Proof. By contradiction. Suppose otherwise in an optimal schedule π, there exists at least one job J_j for some $1 \leqslant j \leqslant n$ with $S_j > r_j$. Construct another preemptive schedule π' by inserting the processing of J_j at time r_j with a time length of zero. We observe that such an insertion of zero time length processing makes no change on the processing schedule of job J_j as well as all the other jobs in π. Hence, the completion times of any job except J_j in the two schedules π and π' are the same. For J_j, $S_j = r_j$ in π' due to the insertion of processing while $S_j > r_j$ in π. We conclude that the completion time of J_j in π' is strictly less than that in π by Formula (3). Hence, the total completion time in π' is strictly less than that in π, contradicting the fact that π is an optimal schedule. The lemma follows. □

Based on the above lemma, we propose an optimal algorithm named MRSPT (Modified Shortest Remaining Processing Time) which is formally described below.

Algorithm MSRPT:
At any time when there releases a job J_j, preempt the currently processing job and start to process J_j on the machine with a time length of zero. The algorithm processes jobs by SRPT (Shortest Remaining Processing Time) rule which processes a job with the shortest remaining processing time among all released jobs. Ties are broken arbitrarily.

Below we show that algorithm MSRPT produces an optimal schedule. By Lemma 1 and Formula (3), the completion time of any job J_j is equal to $C_j = C'_j + q_j = C'_j + \gamma r_j$. Since γ and r_j are extraneously given values, minimizing C_j is equivalent to minimizing C'_j. We conclude that the model $1|r_j, prmp, q_{psd}|\sum C_j$ reduces to the classical preemptive problem without *psd* delivery times, i.e., $1|r_j, prmp|\sum C_j$, which can be solved by SRPT rule [1]. Hence, we have the following theorem.

Theorem 1. *Algorithm MSRPT is optimal for $1|r_j, prmp, q_{psd}|\sum C_j$.*