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Common due date assignment and scheduling with a rate-modifying activity to minimize the due date, earliness, tardiness, holding, and batch delivery cost ☆

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ABSTRACT

We consider a single-machine batch delivery scheduling and common due date assignment problem. In addition to making decisions on sequencing the jobs, determining the common due date, and scheduling job delivery, we consider the option of performing a rate-modifying activity on the machine. The processing time of a job scheduled after the rate-modifying activity decreases depending on a job-dependent factor. Finished jobs are delivered in batches. There is no capacity limit on each delivery batch, and the cost per batch delivery is fixed and independent of the number of jobs in the batch. The objective is to find a common due date for all the jobs, a location of the rate-modifying activity, and a delivery date for each job to minimize the sum of earliness, tardiness, holding, due date, and delivery cost. We provide some properties of the optimal schedule for the problem and present polynomial algorithms for some special cases.

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1. Introduction

Meeting due dates is among the most important goals of scheduling. There are many practical situations in which a common due date exists, e.g. in just-in-time production, in assembly scheduling, or in batch delivery. Furthermore, it might be reasonable to assign a common due date to a set of jobs to treat different customers equally. Generally, two situations of due date determination should be distinguished: (i) the common due date is (externally) given or agreed upon and (ii) the common due date is determined (internally) by the company. The latter situation corresponds to the system in which, for some reason (e.g., appointment, technical constraints, etc.), several tasks are to be completed at the same time, e.g., several jobs from the same customer form a single order or the components of a product should be ready by the same time for assembly. In chemical and food production, the common due date model applies if some of the involved substances or components have a limited life span (a "best before" time), which imposes a common due date on the whole mixture or the final product. There are many papers that focus on the common due date assignment problem (e.g., Adamopoulos & Pappis, 1995; Birman & Mosheiov, 2004; Biskup & Jahnke, 2001; Cheng, 1984, 1987, 1989; Cheng, Chen, & Shakhlevich, 2002, 2004, 2007; De, Ghosh, & Wells, 1991; Gordon & Strusevich, 2009; Hsu, Yang, & Yang, 2011; Kahlbacher & Cheng, 1993; Li, Ng, & Yuan, 2011; Min & Cheng, 2006; Mosheiov, 2001; Mosheiov & Yovel, 2006; Ng, Cheng, Kovalyov, & Lam, 2003; Panwalkar, Smith, & Seidmann, 1982; Shabtay & Steiner, 2006). For state-of-the-art reviews of scheduling models considering common due date assignment, as well as practical applications of such models, the reader may refer to Cheng and Gupta (1989), Gordon, Proth, and Chu (2002, 2010), and Lauff and Werner (2004).

All of the above papers treat the delivery cost as either negligible or irrelevant. In other words, they focus on the machine scheduling problem, while ignoring the problem of scheduling the deliveries of the finished jobs. However, delivery cost is a significant cost element in production, whereby the production cost depends not only on when jobs are processed but also when finished jobs are delivered. Thus, as observed by Hermann and Lee (1993), a realistic production scheduling model should include scheduling of both job processing and job delivery. Several earlier papers have considered scheduling models with both job processing and job delivery. Cheng and Kahlbacher (1993) show that the batch delivery problem to minimize the sum of weighted earliness penalty and delivery cost is NP-hard, while the case with equal weights is polynomially solvable. Cheng and Gordon (1994) provide a pseudopolynomial dynamic programming algorithm to solve the problem and show that the case with identical processing times is also polynomially solvable. Hermann and Lee (1993) study

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another batch delivery problem, where all the jobs have a given restrictive common due date. The objective is to minimize the sum of earliness penalty, tardiness penalty, and delivery cost. They provide a pseudopolynomial dynamic programming algorithm to solve the problem. Chen (1996) studies a variant of the problem introduced by Hermann and Lee (1993) where the common due date is not given but a decision variable to be determined, and shows that the problem can be solved in $O(n^5)$ time. Both Hermann and Lee (1993) and Chen (1996) assume that all the early jobs are delivered on time to the customer without any cost, ignoring the possibility that early jobs may be delivered in batches. Shabtay (2010) addresses a single-machine scheduling problem similar to the one studied by Hermann and Lee (1993), where each job is assigned a due date without restrictions. He applies the best delivery strategy to all the jobs (not only to the tardy ones), includes the earliness penalty in the objective function and considers the case of acceptable lead-time. He shows that the problem is NP-hard and presents a polynomial-time solution algorithm for two special cases. Yin, Cheng, Hsu, and Wu (submitted for publication) study a variant of the problem investigated by Chen (1996) by replacing the common due date assumption with a common due window assumption and by allowing the delivering of the early jobs in more than one batch in the objective function. They show that the problem can be optimally solved in $O(n^8)$ time and that some special cases of the problem can be optimally solved by lower order algorithms.

In this paper we extend the problem studied by Chen (1996) to the cases where holding cost is included in the objective function and an additional rate-modifying activity is allowed. This activity requires a fixed time interval during which the machine is turned off and production stops. On the other hand, after the rate-modifying activity, the machine becomes more efficient, so the jobs processed after the activity have shortened processing times. Scheduling a rate-modifying activity becomes a popular topic among researchers in the last decade. Lee and Leon (2001) study several single-machine scheduling problems in this class to minimize the makespan, flowtime, weighted flowtime, and maximum lateness. Lodree and Geiger (2010) investigate scheduling with a rate-modifying activity under the assumption that a job's processing time is time-dependent. For the sequence-independent, single-machine makespan problem with position-dependent processing times, they prove that under certain conditions, the optimal policy is to schedule the rate-modifying activity in the middle of the job sequence. Mosheiov and Sidney (2004) study the problems to minimize the makespan with precedence relations, the makespan with learning effects, and the number of tardy jobs. Mosheiov and Oron (2006) consider common due date assignment and single-machine scheduling with the possibility of performing a rate-modifying activity on the machine that changes the processing times of the jobs scheduled after the activity. The objective is to minimize the total weighted sum of earliness, tardiness, and due date cost. They provide an $(O(n^4))$ algorithm to solve the problem. Gordon and Tarasevich (2009) further address the problem studied in Mosheiov and Oron (2006). They provide several properties of the problem, which in some cases reduce the complexity of the solution algorithm. Zhao, Tang, and Cheng (2009) consider parallel-machine scheduling with rate-modifying activities. For the problem to minimize the total completion time, they provide a polynomial algorithm to solve it. For the problem to minimize the weighted completion time, they provide a pseudopolynomial dynamic programming algorithm to solve the case where the jobs satisfy an agreeable condition. Wang and Wang (2010) consider single-machine scheduling with assignable slack (SLK) due dates and a rate-modifying activity to minimize the total earliness, tardiness, and common flow allowance cost. They give a polynomial-time solution for the problem. Yin, Cheng, Wu, and Cheng (submitted for publication) study a problem similar to that studied in this paper with a different objective of finding a common due date for all the jobs, a location of the rate-modifying activity, and a delivery date for each job to minimize the sum of earliness cost, weighted number of tardy jobs, holding cost, due date penalty, and delivery cost. Under the assumption that the earliness and holding costs are proportional to their corresponding durations, they investigate the structural properties of the optimal schedule of the problem and present polynomial algorithms for three special cases.

Our problem considered in this paper includes scheduling decisions on (i) the job sequence, (ii) the common due date, (iii) the rate-modifying activity, and (iv) the delivery date for each job, so as to minimize the sum of earliness, tardiness, holding cost, due date, and delivery cost. The rest of the paper is organized as follows: In Section 2 we introduce and formulate the problem. In Section 3 we provide some properties of the optimal schedule. In Section 4 we develop polynomial algorithms for some special cases of the problem. We conclude the paper and suggest some topics for future research in the last section.

2. Model formulation

In this section we first introduce the notation to be used throughout the paper, followed by formulation of the problem.

n	The number of jobs ($n \geqslant 2$)
p_j	The processing time of job J_j
d	The common due date to be determined for all the jobs, i.e., $d_j = d$
ψ_j	The modifying rate of job J_j ($0 < \psi_j \leqslant 1$)
C_j	The completion time of job J_j
D_j	The delivery time of job J_j ($D_j \geqslant C_j$)
$E_j = \max\{0, d - D_j\}$	The earliness of job J_j
$T_j = \max\{0, D_j - d\}$	The tardiness of job J_j
$H_j = D_j - C_j$	The holding time of job J_j, which is the time between the moment the job finishes its processing and the moment it is delivered
α	The unit cost of earliness
β	The unit cost of tardiness
γ	The unit due date assignment cost
θ	The unit cost of holding a job
δ	The constant batch delivery cost

where $j = 1, 2, \ldots, n$. In what follows, given any sequence S, we use the subscript $[j]$ to denote the job in position j of sequence S.

Assume that there is a set of independent jobs $N = \{J_1, J_2, \ldots, J_n\}$ to be processed on a single machine. The machine can handle at most one job at a time and job preemption is not allowed. All the jobs are available for processing at time zero. The jobs are to be delivered in batches to customers. We assume that there is no capacity limit on each batch delivery and that the cost per delivery is fixed, i.e., the cost is independent of the number of jobs delivered in a batch. Hence, it may be beneficial to delay the shipping of a job until the delivery time of the next job because the delay saves a delivery charge. The scheduler also has an option to perform a rate-modifying activity on the machine. The rate-modifying activity is denoted by rm, and the starting time and the length of rm are denoted by s_{rm} and t, respectively. When the machine is undergoing rm, no production is possible. The processing time of job J_j is p_j if the job is processed prior to rm, and $\psi_j p_j$ if it is scheduled after it, $j = 1, 2, \ldots, n$. The objective is to determine (i) the job sequence, (ii) the common due date for all the jobs, (iii) the time (location) to schedule the

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