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Integrated production and job delivery scheduling with an availability constraint☆

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ABSTRACT

In this paper we study the scheduling problem that considers both production and job delivery at the same time with machine availability considerations. There are two parallel machines, where one machine is not available during a time period. Only one vehicle is available to deliver jobs in a fixed transportation time to a distribution center. The vehicle can load at most c jobs as a delivery batch in one shipment due to the vehicle capacity constraint. The objective is to minimize the time by which all jobs are delivered. We consider both resumable and nonresumable cases. For each case, we propose an approximation algorithm with a worst case ratio of 3/2.

1. Introduction

Supply chain management has been one of the most important and widely discussed topics in manufacturing research over the last twenty years. A supply chain represents all stages at which value is added to a manufactured product. Generally speaking, it includes all the interactions between suppliers, manufacturers, distributors, and customers. Due to market globalization, coordination among different stages in the supply chain to achieve ideal overall system performance has become more practical and has received attention from both industry practitioners and academic researchers.

In the literature, much research has focused on the area of integrating scheduling and job delivery. The most recent review and extensions for this area was given by Chen (2010). Here we will survey some important research related to our problem for scheduling with transportation considerations. Hall and Potts (2003) considered a variety of scheduling, batching and delivery problems within a supply chain and minimized the overall scheduling and delivery cost. Transportation capacity was not considered in their models. Lee and Chen (2001) studied the problem that considers machine scheduling and job delivery together. Jobs are delivered to a regional distribution center in batches by vehicles. Both transportation times and vehicle capacity were considered in their models. Chang and Lee (2004) extended Lee and Chen's work to the situation where jobs have different physical spaces to be loaded in the vehicles. Zhong et al. (2007) presented some improved approximation results for the problems considered by Chang and Lee (2004). Lu et al. (2008) considered the situation where each job has a different release date and an identical size. They showed this problem is also strongly NP-hard even when a vehicle can transport one job at one time. Liu and Lu (2011) gave an improved approximation algorithm for the same problem. Wan and Zhang (2014) considered scheduling on m parallel identical machines with v identical transporters that can carry up to c jobs in one shipment. They showed that the problem is NP-hard in the strong sense if m is part of the input and proposed a $(2-1/m)$-approximation algorithm.

In the above mentioned models, the machines are always available for processing jobs over the production period. However, these models are too ideal to handle various restrictions that may occur in practical scheduling. Thus, their extensions that involve additional constraints are of strong interest. One of the extensions of standard scheduling models is related to the so-called machine availability constrains and has received considerable attention since the beginning of the 1990s. In these models, a processing machine is not necessarily continuously available throughout the planning period. Lee (1996) studied single-machine and parallel machine scheduling problems with an availability constraint. For various performance measures, he developed pseudo-polynomial dynamic programming algorithms to solve the problem optimally or provided heuristics with error bound analysis. Lee and Chen (2000) studied parallel machine scheduling problems where each machine is maintained once during the planning period. To learn

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more about research results on this aspect, the reader is referred to the review papers by Lee et al. (1997), Schmidt (2000) and Ma et al. (2010).

Wang and Cheng (2007) introduced the machine availability constraint into integrated scheduling with production and transportation. In this paper, we reinvestigate the problems studied by Wang and Cheng (2007). This problem can be formally stated as follows. We are given a set of n jobs, $J=\{J_1, J_2, \ldots, J_n\}$, which are to be first processed in a manufacturing center and then delivered to a distribution center. Only one vehicle is available for delivering the jobs, which can load at most c jobs in one shipment. The vehicle is initially at the manufacturing center and available for delivery. All the jobs delivered together in one shipment are defined as a delivery batch. Associated with each delivery batch is T, which is the round-trip transportation time between the manufacturing center and the distribution center. The objective is to minimize the time at which the vehicle finishes delivering the last batch and returns to the manufacturing center. In the manufacturing center, there are two identical parallel machines. We assume that there exists an unavailable interval on one of the machines while the other machine is always available over the production period. Each job J_i requires a processing time of p_i and can be processed on either machine.

We follow the notation of Lee and Chen (2001) to denote the problems under study, with extensions to include availability constraints. The problems under study are denoted by $P2 \rightarrow D, h_{11} \mid r-a, v=1, c \geq 1 \mid D_{max}$ and $P2 \rightarrow D, h_{11} \mid nr-a, v=1, c \geq 1 \mid D_{max}$, respectively. In the α field, we use $P2 \rightarrow D$ to represent problems where jobs are first processed on two parallel machines and then delivered to the customer. h_{11} means that there is only one unavailable interval on machine M_1. In the field β, $r-a$ denotes that jobs interrupted by the unavailable interval can resume processing after the machine again becomes available, while $nr-a$ denotes that interrupted jobs must restart processing after the machine again becomes available. $v=1$ denotes there is only one vehicle available and $c \geq 1$ denotes the vehicle can transport at most $c \geq 1$ jobs in one shipment. In the γ field, D_{max} denotes the time at which the vehicle returns to the manufacturing center after delivering the last batch to the distribution center. It is clear that our problems are more general than $P2 \| C_{max}$. Therefore, both problems are obviously NP-hard. So it is justifiable to develop heuristics for both problems. In this paper, for the resumable case, we develop a 3/2-approximation algorithm, which improves upon the worst-case bound 5/3 of the heuristic presented by Wang and Cheng (2007). For the non-resumable case, we propose a 3/2-approximation algorithm, which is the first heuristic for the problem.

The remainder of the paper is organized as follows. In Section 2 we introduce some notation and give some preliminaries. In Section 3 we propose a heuristic for the resumable case and analyze its worst case ratio. Then we present an approximation algorithm to solve the nonresumable case in Section 4. Finally, some concluding remarks are give in Section 5.

2. Preliminaries

First, we introduce some notation which will be used throughout this paper:

M_j: machine $j, j=1,2$;
UI $=[B, F]$: Unavailable Interval (UI) on M_1 from time B to F;
$\Delta=F-B$: the length of UI;
σ: a schedule generated by a heuristic.
σ^*: an optimal schedule.
T: the round-trip transportation time between the manufacturing center and the distribution center.

Unless confusion would occur, we use C_j, C_j^* to denote the completion time of J_j in σ, σ^*, respectively. We use $J_{[j]}, J_{[j]}^*$ to denote the jth completion job in σ, σ^*, respectively. We use $p_{[j]}, C_{[j]}$ to denote the processing time, the completion time of $J_{[j]}$ in σ, respectively. We use $p_{[j]}^*, C_{[j]}^*$ to denote the processing time, the completion time of $J_{[j]}^*$ in σ^*, respectively. For convenience, we assume that $(\sum_{i=1}^{n} p_i)/2 \geq B$. Thus $C_{[n]}^* \geq B$.

For both resumable case and non-resumable case, the following optimal property holds.

Property 1 (*Wang and Cheng (2007)*). *There exists an optimal solution that satisfies the following properties*:

(i) *The jobs should be processed as early as possible in a schedule.*
(ii) *If there exist available delivery batches, then the vehicle should not be idle.*
(iii) *A job with an earlier ready time for delivery is delivered no later than that with a later ready time.*
(iv) *Each delivery batch, except the first delivery batch, contains exactly c jobs.*

Proof. (i) and (ii) is obvious.

(iii) It can easily be proved by the swapping argument.
(iv) Suppose that there exists an optimal solution π which does not satisfy (iv). Without loss of generality, suppose there are $m \geq 2$ delivery batches in π. Index the m delivery batches as $B_1, B_2, \ldots, B_m$ in the non-decreasing order of their delivery times. Let B_k ($k \geq 2$) be the last delivery batch containing less than c jobs, i.e., $|B_m| = |B_{m-1}| = \cdots = |B_{k+1}| = c$ and $|B_k| = h < c$. We put the last finished job of B_{k-1} into B_k to generate a new solution π' with delivery batches $B_1, \ldots, B'_{k-1}, B'_k, \ldots, B_m$, where $|B'_k| = h+1$ and $|B'_{k-1}| = |B_{k-1}| - 1$. Clearly, the ready time of each delivery batch in the new solution is not greater than that in π, so $D_{max}(\pi') \leq D_{max}(\pi)$. Repeat the above procedure and we can obtain an optimal solution which satisfies (iv).□

Based on the above property, we can give the following lower bound for any optimal schedule.

Lemma 1. *$D_{max}^* \geq C_{[j]}^* + (q_j+1)T$, where $q_j = \lfloor (n-j)/c \rfloor$, $1 \leq j \leq n$.*

Proof. In the optimal schedule, by time $C_{[j]}^*$, there are at least $n-j+1$ jobs which have not been delivered. The vehicle delivers at most c jobs in one delivery batch. Thus there are at least q_j+1 batches when the vehicle delivers the $n-j+1$ jobs, where $q_j = \lfloor (n-j)/c \rfloor$. The earliest departure time of the q_j+1 batches is time $C_{[j]}^*$. The round-trip transportation time between the manufacturing center and the distribution center is T. Therefore, $D_{max}^* \geq C_{[j]}^* + (q_j+1)T$.□

3. The resumable case

We now consider the resumable case, i.e., an unfinished job can resume processing after M_1 becomes available again after the unavailable interval. For this case, Wang and Cheng (2007) presented a 5/3-approximation algorithm. In this section, we will present an improved algorithm with an error bound of 1/2.

We first introduce the approximation algorithm. In the following heuristic, for convenience, we list the jobs in nondecreasing order of their processing times and without loss of generality, denote the list by $L=[J_1, J_2, \ldots, J_n]$. Let J_u be the first job in L such that $\sum_{i=1}^{u} p_i > B$.