Int. J. Production Economics 132 (2011) 223–229

Contents lists available at ScienceDirect

Int. J. Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Supply chain scheduling and coordination with dual delivery modes and inventory storage cost

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ARTICLE INFO

Article history:
Received 12 February 2010
Accepted 8 April 2011
Available online 27 April 2011

Keywords:
Flow shop scheduling
Supply chain scheduling
Time window
Dynamic programming
Channel coordination

ABSTRACT

We study a two-echelon supply chain scheduling problem in which a manufacturer acquires supplies from an upstream supplier and processes orders from the downstream retailers. The supply chain sells a single short-life product in a single season. We consider the scenario where the manufacturer can only accept some of the orders from the retailers due to its supplier's common production time window and its own two common production and delivery time windows. The upstream supplier processes materials and delivers the semi-finished products to the manufacturer within its time window. Then the manufacturer further processes these products to produce finished products and delivers them to the retailers within its two time windows, where one window is for production and normal delivery, and the other is for production and express delivery. Having to store the materials before processing them, the supplier incurs a storage cost, which depends on the order size and storage time. The manufacturer pays the transportation cost for delivering the finished products to the retailers. Due to double marginalization, the performance of the supply chain is sub-optimal. We model the supply chain problem as a flow shop scheduling problem with multiple common time windows. We derive some dominance properties and establish some theorems that help solve the sequencing problems for the orders and eliminate the idle time among the orders. Based on these results, we develop fast pseudo-polynomial dynamic algorithms to optimally solve the problem. We prove that the problem is NP-hard in the ordinary sense only. We develop two practically relevant and robust methods for the supply chain to achieve optimal profit-making performance through channel coordination.

1. Introduction

Scheduling problems in the two-echelon supply chain are challenging due to their combinatorial nature. The reason is that as the number of possible schedules for the problems is huge, the time required to solve the problems is prohibitively long (Blazewicz et al., 2001). Hence it is important to develop fast algorithms to produce solutions under reasonably restricted conditions. In a decentralized supply chain, individual parties have their own profit structures. Thus they make decisions that maximize their own profits and this will usually lead to a sub-optimal supply chain. In this paper we consider a supply chain that has an upstream supplier (M_1) and a downstream manufacturer (M_2), where M_2 accepts some of the n orders J_i ($i=1,2, \ldots, n$) from n retailers. Specifically, in our problem, we consider a supply chain that sells a short-life product in a single season, where the product requires a long production lead-time. Hence each retailer only places a single order with M_2 and it has no re-ordering opportunity. To process an order J_i with time $p_{i,2}$ from a retailer, M_2 needs to first acquire semi-finished products from M_1, which has processed the materials with time $p_{i,1}$, $i=1,2, \ldots, n$. Then M_2 further processes the semi-finished products to produce the finished products. All the orders are available at time 0 and they share a common selling season. We assume that both M_1 and M_2 adopt the make-to-order strategy. Due to production capacity limits in the supply chain, e.g., production manpower and machines are limited, each of M_1 and M_2 can only process one order at a time, and M_2 cannot accept all of the retailers' orders.

The retailers specify the due date of receiving the finished products such that the latest common delivery start time for the manufacturer's normal delivery is d_2. The express delivery is used when the normal delivery cannot meet the receiving due date, where the express delivery time window is given by $(d_2,d_3]$ such that the latest common delivery start time for the manufacturer's express delivery is d_3. Note that the receiving due date is later than d_2 and d_3. We consider that M_2 starts to deliver the finished products no later than d_2 in the normal delivery mode and starts

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doi:10.1016/j.ijpe.2011.04.012

to deliver the products within $(d_2,d_3]$ in the express delivery mode because any delay will cause a substantial loss of profit to the retailers and M_2 will suffer from a substantial loss of goodwill. In addition, M_1 must (i) finish processing the materials no later than d_1 and then (ii) immediately deliver the semi-finished products to M_2 after processing the materials, where the given parameter d_1 is less than the parameter d_2. Also, M_1 needs to store the materials before processing them, and the storage cost depends on the sizes of the orders and the time of storing the materials. The size of an order q_i is agreeable with its processing time $p_{i,1}$ on M_1, $i=1,2,\ldots,n$ (i.e., $q_1 \le q_2 \le \cdots \le q_n$ implies $p_{1,1} \le p_{2,1} \le \cdots \le p_{n,1}$). Thus the storage cost for storing the materials before processing on M_1 is measured by $\theta q_i s_{i,1}$, where θ and $s_{i,1}$ are the storage cost per unit quantity per unit time and the start time of processing order $J_{i,1}$ on M_1, $i=1,2,\ldots,n$, respectively (the storage time is the time duration between time 0 and $s_{i,1}$). Moreover, we consider the scenario where the production lead (processing) times have been reduced to the minimum so they are the given parameters (not decision variables). Thus we focus on minimizing the transportation cost rather than the production lead times. Regarding the transportation cost, we assume that the distance between M_1 and M_2 is short so the transportation lead time between M_1 and M_2 and the associated transportation cost is negligible. However, the distance between M_2 and retailer i is long, so a substantial transportation cost is incurred. This transportation cost of order J_i is $q_i\alpha_i$, which depends on the size of the order (quantity) q_i and the mode of delivery between M_2 and retailer i, where the normal transportation cost per unit quantity is α_i and the express transportation cost per unit quantity is β_i, $i=1,2,\ldots,n$. We assume that all the retailers are located in the same geographical zone as far as the transportation cost is concerned. Hence the distances between the manufacturer and the retailers need not be expressed explicitly in our problem because the same zone-to-zone distance is already incorporated into α_i and β_i for $i=1,2,\ldots,n$. In order to maximize the profit by accepting more orders, M_2 uses the express delivery mode of transport to deliver the finished products, which is charged at a higher unit transportation cost, so $\beta_i > \alpha_i$, $i=1,2,\ldots,n$.

The problem is motivated by a supply chain problem commonly found in apparel production, where M_2 is a garment factory (in a developing country such as China) that produces apparel products and M_1 is a textile company (which is located closely to M_2) that supplies the fabrics for M_2. The retail buyers, such as those from national fashion brands, are usually located in the developed countries in North America and Europe. The issue of transportation cost (and time) as described above hence arises. In order to fulfill the retail buyers' orders, e.g., a certain quantity of polo shirts, M_2 needs to perform production operations such as cutting, assembly, quality checking, etc, whereas M_1 needs to perform the operation of dyeing (e.g., from gray yarn). In this setting, the production (processing) time of an order at M_2 (called an M_2-order) is usually longer than that of the order at M_1 (called an M_1-order) because for M_1 dyeing is rather straightforward and the required time increases with the quantity of gray yarn. Obviously, for M_2, the production time also increases with the ordered quantity of polo shirts. As a consequence, the production times of M_1 and M_2 are agreeable because a larger order requires a longer production time, i.e., mathematically the processing times of orders J_i and J_k satisfy the following condition: if $p_{i,1} < p_{k,1}$, then $p_{i,2} < p_{k,2}$, for $i,k=1,2,\ldots,n$ $(i \ne k)$, where $p_{i,1} < p_{i,2}$ for all $i=1,2,\ldots,n$ (since making garment to fulfill an M_2-order takes a longer time than dyeing the fabrics for the corresponding M_1-order). We note that the processing time of an M_1-order can be longer than that of another M_2-order due to the larger size of that specific M_1-order, so idle time may be incurred on M_2. In addition, for many garment factories, in order to meet the due date requirements specified by the retailers, they could consider using the express delivery. Despite being relatively costly, this has become a common industrial practice, given the importance of meeting customer (retailers') due dates and the relatively lower transportation costs of express delivery when manufacturers form strategic alliances with logistics companies and garment factories.

With the industrial motivation and the problem setting presented above, we formulate the above problem as a two-machine multiple common time windows flow shop scheduling problem, in which the first machine is M_1 and the second machine is M_2. We first analytically explore the decentralized case where M_2 is the decision maker, which determines the optimal order set and the optimal schedule of the orders to process so that its profit is maximized. We then study the centralized case, in which a supply chain coordinator (M_2 or M_1) exists that strives to find the best schedule for the whole supply chain. We prove that all the decentralized and centralized cases are NP-hard in the ordinary sense only.

The two-machine flow shop scheduling problem has been widely studied in the literature. For example, Jozefowska et al. (1994) consider the problem to minimize the weighted number of tardy jobs with a common due date. They prove that the problem is NP-hard in the ordinary sense. Della Croce et al. (2000) investigate the problem to minimize tardiness with equal weights. They devise a branch-and-bound algorithm to find an optimal solution for the problem. Yeung et al. (2004) consider the problem to minimize earliness and tardiness with a common due window. They show that the problem is strongly NP-hard, and develop a branch-and-bound algorithm and a heuristic algorithm to solve the problem. Most recently, Yeung et al. (2010) studied the optimal scheduling of a single-supplier single-manufacturer supply chain with common due windows. They show that the problem is NP-hard and develop a pseudo-polynomial algorithm to optimally solve the problem. They develop a method that eliminates the need for generating all the optimal partial schedules to obtain an optimal solution, thus reducing the running time for solving the problem. For a survey on research and some updates related to flow shop scheduling problems, we refer the reader to Gupta and Stafford (2006) and Qi (2011). All these works provide us with the foundation to study related scheduling problems in supply chain management. Unlike the problems in the literature, our model incorporates the transportation issue involving two delivery time windows and dual transport delivery modes. The model is challenging because it requires a fast algorithm to solve the problem in real life. This may be the reason why there is a lack of optimal solution algorithms for the problem in the literature. In addition, fast optimal algorithms are required to maximize the efficiency of channel coordination in the supply chain without a closed-form solution. The solution algorithms developed in this paper fill this gap.

In the context of multi-echelon supply chain management, many channel coordination schemes have been proposed in the literature to deal with challenges such as double marginalization.[1] Some coordination methods are also motivated by the industrial cases with short-life fashionable products (e.g., Chen and Xu, 2001; Liu et al., 2006; Wei and Choi, 2010). Methods for coordinating inventory decisions in a multi-echelon supply chain include the returns policy, sales rebates (Chiu et al., 2011), quantity discounts scheme (Xiao et al., 2007), price-subsidy policy

[1] Double marginalization refers to the case that an individual supply chain agent and the whole supply chain have different profit margins (there are two different margins). This directly and naturally leads to the case that the optimal decision for an individual supply chain agent differs from the supply chain's global optimal solution. Please refer to Spengler (1950) for more discussions.