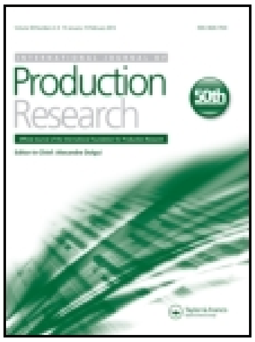

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Scheduling and co-ordination of multi-suppliers single-warehouse-operator single-manufacturer supply chains with variable production rates and storage costs

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We study a supply chain scheduling and co-ordination problem comprising multiple suppliers, a single warehouse operator, a single manufacturer, and multiple retailers, where the supply chain has limited production capacity that can take only some of the orders from the retailers. For a decentralised supply chain, the manufacturer is a decision maker that selects the orders and aims to maximise its own profit, where the profit is a function of the order storage time and storage quantity, order sequence-dependent weighted storage costs, and idle time of the orders. On the other hand, for a centralised supply chain, a supply chain co-ordinator exists that aims to maximise the profit of the whole supply chain and allocates the profit among the supply chain members. We first formulate the problem as a two-machine common-due-window flow shop scheduling problem. We then develop a theorem and two algorithms to solve the optimal scheduling problems in both the decentralised and centralised supply chains. With these results, we develop a method that can achieve channel co-ordination based on a profit sharing rule, together with an increase in the production rates and a decrease in the storage costs.

Keywords: flow shop scheduling; production rate; storage cost; supply chain co-ordination

1. Introduction

The supply chain scheduling and co-ordination (SCSC) problem is a critical problem in supply chain management (Chan and Chan 2010). It is especially challenging in a distributed network (Chung *et al.* 2009). In this paper we study a SCSC problem in which the supply chain consists of multiple suppliers, a single warehouse operator, a single manufacturer, and multiple retailers. We consider the case where the supply chain has limited production capacity and it only accepts some of the orders from the retailers. We consider both the centralised and decentralised supply chains. By formulating the problem as a two-machine common-due-window flow shop scheduling problem, we develop solution algorithms and propose a co-ordination scheme to achieve supply chain optimisation for the decentralised model.

This paper can be regarded as an extension of the supply chain scheduling problem of maximising profit with storage costs studied by Yeung *et al.* (2010), who consider the problem with a single supplier, a single manufacturer, and multiple retailers, where the supply chain has limited production capacity and thus can take only some of the orders from the retailers. They formulate the problem as a two-machine flow shop scheduling problem in which the supplier's and manufacturer's orders are processed on the first machine (M_1) and the second machine (M_2), respectively. Let the processing time of order $J_i \in N$ on M_1 be $p_{i,1}$ and the processing time of order $J_i \in N$ on M_2 be $p_{i,2}$, where $N = \{J_1, J_2, \ldots, J_n\}$ is a set of the orders of the retailers. They assume that there are proportionate relationships between the processing times of the orders on M_1 and M_2 such that the processing times of J_i and J_k satisfy $p_{i,2}/p_{i,1} = p_{k,2}/p_{k,1} = \beta > 1$ for all $J_i, J_k \in N$ $(i \neq k)$, where β is a proportionate constant (i.e. the processing times on M_2 and M_1 are in proportion and $p_{i,2} > p_{i,1}$ for all $J_i \in N$). Their objective is to maximise the profit of the manufacturer, where the profit is a function of the storage time, storage quantity, order sequence-dependent storage costs, and idle time of the orders. They show that the problem is NP-hard and develop an algorithm that can solve large-sized instances of the problem very efficiently.

In this paper we extend Yeung *et al.* (2010)'s problem in three ways: first, we extend the single-supplier scenario to $m(m \geq 2)$ suppliers. Second, we explore the issue of channel co-ordination in the supply chain. Furthermore, in

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the multiple suppliers' scenario, we consider (1) the case where individual suppliers possess different expediting machines for producing the supplies at different production rates and (2) the case where a higher production rate of the expediting machine implies that the supplier will charge the manufacturer a higher price for the supplies. Third, M_2 integrates with the warehouse operator to make its operations so efficient that the storage costs of the produced supplies are reduced.

To be specific, in the supply chain we investigate in this paper, there are $m(m \geq 2)$ upstream suppliers represented by the set $H = \{S_1, S_2, \ldots, S_m\}$ and a downstream manufacturer M_2, which selects the best subset N' of the order set N ($N' \subset N$) from n retailers. On one hand, to produce the products for the retailers, M_2 first orders supplies from supplier $S_j \in H$ and integrates with the warehouse for reducing the storage costs of the supplies, where the retailers specify the latest common delivery due date d_2 for the products; then M_2 must complete processing of its orders from N' within the due window $[0, d_2]$ to meet the due date. On the other hand, $S_j \in H$ must complete processing of the orders of supplies within the due window $[0, d_1]$ specified by M_2, where the processing time p_i^j on the expediting machine $S_j \in H$ is shorter than the normal processing time $p_{i,1}$ on the standard machine M_1 for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$; thus $S_j \in H$ can charge M_2 a higher price of the supplies. After finishing processing its supplies, $S_j \in H$ immediately delivers them to the integrated warehouse operator, which stores them until M_2 requires further processing. M_2 pays the reduced storage costs, which vary with the selection and sequence of the orders, and the idle time, storage time, and sizes of the orders. This storage cost per J_i is measured by $\gamma_i^j(s_{i,2} - c_i^j)$ when the expediting machine is used and the integrated warehouse is considered in the centralised supply chain for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$. Similarly, this storage cost per J_i is measured by $\gamma_i(s_{i,2} - c_{i,1})$ when the standard machine is used and the non-integrated warehouse is considered in the decentralised supply chain for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$, where:

- $\gamma_i^j = \alpha' \phi^j p_i^j$ ($\gamma_i = \alpha \phi p_{i,1}$) = storage cost per J_i per unit storage time at the integrated (non-integrated) warehouse for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$;
- $\alpha'(\alpha)$ = storage cost per unit storage time per unit of the supplies at the integrated (non-integrated) warehouse, where $\alpha' < \alpha$;
- $\phi^j(\phi) = S_j'$s (M_1's) production rate of the expediting (standard) machine, where $\phi^j > \phi$ for $j = 1, 2, \ldots, m$;
- p_i^j ($p_{i,1}$) = S_j's(M_1's) processing time of J_i on the expediting (standard) machine, where $p_i^j < p_{i,1}$ for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$;
- $\phi^j p_i^j$ ($\phi p_{i,1}$) = quantity of J_i produced by S_j (M_1) using the expediting (standard) machine for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$;
- $s_{i,2}$ = start time of J_i on M_2 for $i = 1, 2, \ldots, n$;
- c_i^j ($c_{i,1}$) = completion time of J_i on S_j (M_1) for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$.

We consider both the decentralised and centralised supply chains for our problem. For the decentralised supply chain, the manufacturer is a decision maker that determines which suppliers to select, which orders to accept, what schedule to process the orders, and how to minimise idle time and storage costs in order to maximise its own profit regardless of the profits of the other supply chain members. For the centralised supply chain, a supply chain co-ordinator exists that determines all those similar to what the manufacturer does in the decentralised supply chain, but the co-ordinator aims to maximise the profit of the whole supply chain and to co-ordinate the supply chain members for improving the efficiency of the supply chain under a contract of profit sharing.

Real-world examples of our problem can be found in many industries such as in apparel production. As an example, M_2 is a garment factory and $S_j \in H$ are multiple fabrics providers and the problem is to maximise the profits of the suppliers, the manufacturer, or the whole supply chain with channel co-ordination. For more details on the motivation of our problem, the interested reader may refer to Yeung *et al.* (2010).

The rest of the paper is organised as follows: we review the literature in the next section. Then we model our problem in Section 3. We present a solution approach to the problem in Section 4 and a method of channel co-ordination in Section 5. To show the effectiveness of the proposed method, we conduct computational experiments and present the results in Section 6. We conclude the paper in the last section.

2. Literature review

The flow shop scheduling problem has been widely studied in the literature. We review the related flow shop scheduling problems of minimising costs of earliness, tardiness and inventory as follows: Della Croce *et al.* (2000)

investigate the common-due-date problem to minimise the number of tardy jobs. They assume that if a job completes later than the due date, a tardiness penalty will be incurred. They develop a branch and bound algorithm to solve large-sized instances of the problem. Bulbul *et al*. (2004) consider the m-machine ($m \geq 2$) flow shop scheduling problem to minimise the weighted earliness, tardiness, and inventory holding costs. They show that the problem is NP-hard in the strong sense and develop a heuristic for the problem. They provide computational results to show that the heuristic is fast and can generate near-optimal solutions for large-sized instances of the problem. Behnamian *et al*. (2010) study the problem of minimising the earliness and tardiness in a hybrid flowshop with sequence-dependent setup times. They develop an efficient and effective hybrid meta-heuristic for this strongly-NP-hard problem. Their computational results show that the algorithm is computationally more effective in yielding better solutions than the adapted random key genetic algorithm and the immune algorithm in the literature.

Ow (1985) introduces a special class of the flow shop in which the processing times of the jobs are proportionate. We review research on the proportionate flow shop with different machine speeds as follows: Hou and Hoogeveen (2003) consider the three-machine proportionate flow shop problem to minimise the makespan with unequal machine speeds. They show that the problem is NP-hard in the ordinary sense. Choi *et al*. (2006) study the problem of minimising the total weighted completion time in the two-machine proportionate flow shop, where the job processing times are inversely proportional to the machine speeds. They show that the problem is NP-hard and propose a heuristic for the problem. Their computational study shows that the performance of the heuristic is good. Choi *et al*. (2007) consider the m-machine ($m \geq 2$) proportionate flow shop problem to minimise the makespan with one machine having an unequal speed. They show that the problem is NP-hard and provide two good heuristics for the problem.

In the context of supply chain scheduling and co-ordination, we review the following papers. Hall and Potts (2003) consider a number of scheduling, batching, and delivery supply chain problems. Their objective is to minimise the total scheduling and delivery cost that involves several classical performance measures. They either construct efficient dynamic programming algorithms to solve the problems or show that the problems are intractable. They also consider the co-operation between a supplier and a manufacturer to reduce the system-wide cost. They identify incentives and mechanisms for co-operation to improve the efficiency of the supply chain. Tsay *et al*. (1999) review model-based research on incentive alignment contracts in the supply chain setting. They provide the first comprehensive description and classification of model-based analyses of contracts for co-ordinating supply chains. Cachon (2003) reviews and extends the supply chain co-ordination literature on the use of contracts, where a number of supply chain models are discussed. Various contract types are identified and their benefits and drawbacks are illustrated. Li and Xiao (2004) consider the problem with lot streaming, where the machines in a multiple-stage production process are owned and managed by different companies. They develop and analyse co-ordination mechanisms that make the different companies to co-ordinate their lot splitting decisions so that they can achieve a global optimum. Hall and Potts (2005) address a couple of scheduling problems in which deliveries are made in batches to the customer. The objectives of the problems are to minimise some scheduling costs and delivery costs in single- and parallel-machine environments. They show that some problems are NP-hard and provide algorithms to minimise the total cost. Their work has significant implications for the co-ordination of scheduling with batch delivery decisions to improve customer service. Chen and Pundoor (2006) study several supply chain problems in which a manufacturer produces a variety of time-sensitive products that have a short life cycle, which are sold in a very short selling season. The objectives of the problems are to minimise the total lead time, maximum lead time, and total cost, where the processing times and order costs depend on the plant to be assigned. They show that the problems are NP-hard and develop several heuristics for generating near-optimal solutions quickly. Dawande *et al*. (2006) study two supply chain problems where one problem is to minimise customer cost and the other problem is to minimise inventory holding cost. Their problems consider several scenarios about the level of co-operation between the manufacturer and distributor. They provide algorithms for the problems and demonstrate that the cost saving resulting from the co-operation is significant. Chen and Hall (2007) consider an assembly system in which suppliers provide parts to a manufacturer and a product cannot be delivered until all its parts have been supplied. Two supply chain scheduling problems are examined. One problem is to minimise the total completion time and the other problem is to minimise the maximum lateness. They consider four scenarios for the relative bargaining power of the suppliers and the manufacturer, and in each case describe a practical mechanism for achieving co-operation between the decision makers. They show that some cases are intractable and develop heuristics for them. They demonstrate computationally that the cost saving realised by co-operation between the decision makers is significant in many cases. Tadeusz (2009) considers a supply chain that consists of three stages: manufacturer/supplier providing product-specific parts, producer assembling finished products from customer orders, and customers generating final demand for the products. The problem is to co-ordinate the manufacturing and supply of parts and assembling of products such that the total supply chain inventory holding cost and the production line start-up and parts shipping costs are minimised. He uses a mixed integer programming approach for the problem and reports promising computational results. For some relatively recent works on multi-stage supply chain co-ordination, Xiao *et al.* (2005) develop a price-subsidy contract and show that it can co-ordinate a supply chain in which there are a single manufacturer and multiple retailers. Later on, Xiao *et al.* (2007) derive some supply chain co-ordination mechanisms by employing either a linear quantity discount schedule or an all-unit quantity discount scenario. They illustrate the achievability of supply chain co-ordination and provide important managerial insights on the two different methods. Li and Weng (2007) review co-ordination mechanisms of supply chain systems. They provide a framework that is based on the supply chain decision structure and the nature of demand. The framework focuses on the behavioural aspects and information need in the co-ordination of a supply chain. Recently, Chiu *et al.* (2011) consider a supply chain co-ordination problem involving price-dependent demands; by using a flexible contract consisting of wholesale price, rebate, and returns, they co-ordinate the supply chain with the price-dependent demands. For recent reviews of the supply chain co-ordination literature, the reader may refer to Arshinder *et al.* (2008) and Arshinder *et al.* (2011)

3. Problem formulation

In this section we model our problems as centralised and decentralised supply chain sub-problems. The sub-problem $P1$ ($P2$) refers to the scenario where the supply chain co-ordinator (manufacturer) maximises the profit for the centralised (decentralised) supply chain. For both sub-problems, all the orders are static and deterministic, non-pre-emptive, and available at time 0. Let a_i^j be $M_2's$ profit excluding the storage costs of J_i for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$. Let b_i^j be $S_j's$ profit excluding the storage costs of J_i for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$. We model $P1$ as a two-machine flow shop scheduling problem, where $J_i \in N$ is processed by $S_j \in H$ (M_2) on the first (second) machine of the flow shop:

For each S_j ($j = 1, 2, \ldots, m$), we have

$$\operatorname*{Max}_{\sigma_C^j, U_i^j} Z_C(\sigma_C^j, U_i^j) = \sum_{i=1}^{n} \left[a_i^j + b_i^j - \gamma_i^j (s_{i,2} - c_i^j)\right] U_i^j,$$

subject to $c_i^j \le d_1$, $c_{i,2} \le d_2$, and $s_{i,2} = c_{i,2} - p_{i,2} \ge c_i^j$ for $i = 1, 2, \ldots, n$. If $U_i^j = 1$ ($U_i^j = 0$), then J_i is (not) accepted by the supply chain co-ordinator C, where U_i^j is a binary variable for schedule σ_C^j for $i = 1, 2, \ldots, n$.

In the sub-problem $P1$, $Z_C(\sigma_C^j, U_i^j)$ is a profit function (recall that γ_i^j is defined in Section 1) for $i = 1, 2, \ldots, n$; the first two constraints ensure that (i) the orders processed on $S_j \in H$ (M_2) must complete their processing within $[0, d_1]$ ($[0, d_2]$) and the last constraint ensures that (ii) the processing of the orders on M_2 cannot start until the processing of its corresponding orders on $S_j \in H$ are completed. Similarly, we model $P2$ as follows:

$$\operatorname*{Max}_{\sigma_{M_2}, V_i} Z_{M_2}(\sigma_{M_2}, V_i) = \sum_{i=1}^{n} [a_i - \gamma_i(s_{i,2} - c_{i,1})] V_i,$$

subject to the constraints similar to those for $P1$. If $V_i = 0$ ($V_i = 1$), then M_2 (does not accept) accepts J_i, where $V_i = 1$ is a binary variable for schedule σ_{M_2} and a_i is $M_2's$ profit excluding the storage costs of J_i for $i = 1, 2, \ldots, n$.

4. Solution approach

In this section we first develop a theorem and then two algorithms for solving sub-problems $P1$ and $P2$.

Theorem 1: *The orders J_i and J_k processed on $S_j \in H$ and M_2 satisfy $p_{i,2}/p_i^j = p_{k,2}/p_k^j = \beta^j$, where $\beta^j = \beta/\psi^j$ and $0 < \psi^j < 1$ such that $\phi^j \psi^j = \phi$ is satisfied for $i, k = 1, 2, \ldots, n$ ($i \ne k$) and $j = 1, 2, \ldots, m$.*

Proof of Theorem 1: See Appendix.

Theorem 1 proves that the processing time of each supplier is proportional to the processing time of the manufacturer. For the NP-hardness of $P1$ and $P2$, we recall that the problem studied by Yeung *et al.* (2010) is NP-hard. By Theorem 1, we can use a similar approach employed by Yeung *et al.* (2010), which shows that Problem P is

NP-hard by a reduction from the well-known NP-hard Partition problem, to prove that $P1$ and $P2$ are also NP-hard. Based on these results, we can modify the $O(nd_1d_2P_{\max,1})$ pseudo-polynomial dynamic programming algorithm for the proportionate flow shop scheduling problem presented in Yeung *et al*. (2010) to solve $P1$ and $P2$, where $P_{\max,1}$ is the longest processing time on M_1. We call the modified algorithms Algorithm 1 for $P1$ and Algorithm 2 for $P2$.

Algorithm 1: Maximising the profit in the centralised supply chain

For each $S_j (j = 1, 2, \ldots, m)$, do the following steps:

(1) Sort the orders $J_1, J_2, \ldots, J_n$ in the shortest processing time first (SPT) permutation sequence.
(2) Let the state t_1 (t_2) be the completion time of a partial schedule within the due window, measured from time 0 on $S_j \in H$ (M_2).
(3) Let $f^j(\xi, t_1, t_2)$ be the maximum profit of $S_j \in H$ and M_2, given that the first $J_1, J_2, \ldots, J_{\xi-1}$ orders in stage ξ have already been assigned, such that the orders processed on $S_j \in H$ complete by d_1 and not later than t_1 on $S_j \in H$ and such that the orders processed on M_2 complete by d_2 and not later than t_2 on M_2 for $\xi = 1, 2, \ldots, n$; $t_1 = 0, 1, \ldots, d_1$; $t_2 = 0, 1, \ldots, d_2$.

Initial conditions

$f^j(1, t_1, t_2) = 0$ for $t_1 = 0, 1, \ldots, p_1^j - 1$, and $t_2 = 0, 1, \ldots, d_2$; $t_1 = 0, 1, \ldots, d_1$ and $t_2 = 0, 1, \ldots, p_1^j + p_{1,2} - 1$.

$$f^j(1, t_1, t_2) = \begin{cases} 0, & \text{if } t_1 > t_2 - p_{1,2} \text{ or } \gamma_1^j(t_2 - p_{1,2} - t_1) \geq a_1^j; \\ a_1^j + b_1^j - \gamma_1^j(t_2 - p_{1,2} - t_1), & \text{otherwise} \end{cases}$$

for $t_1 = p_1^j, p_1^j + 1, \ldots, d_1$ and $t_2 = p_1^j + p_{1,2}, p_1^j + p_{1,2} + 1, \ldots, d_2$.

$$f^j(\xi, t_1, t_2) := f^j(\xi - 1, t_1, t_2) \text{ for } \xi = 2, 3, \ldots, n;\ t_1 = 0, 1, \ldots, d_1;\ t_2 = 0, 1, \ldots, d_2.$$

Recursive relations

$$f^j(\xi, t_1, t_2) = \begin{cases} f^j(\xi - 1, t_1, t_2), & \text{if } t_1 - p_\xi^j < 0, t_1 > t_2 - p_{\xi,2} or \gamma_\xi^j(t_2 - p_{\xi,2} - t_1) \geq a_\xi^j; \\ g^j(\xi - 1, t_1, t_2) & \text{otherwise} \end{cases}$$

where

$$g^j(\xi - 1, t_1, t_2) = \max \begin{cases} f^j(\xi - 1, t_1 - p_\xi^j, t_1 - i) + a_\xi^j + b_\xi^j \\ \text{if } t_1 = t_2 - p_{\xi,2} \text{ for } i = 0, 1, \ldots, p_\xi^j - 1; \\ f^j(\xi - 1, t_1 - p_\xi^j, t_2 - p_{\xi,2}) + a_\xi^j + b_\xi^j - \gamma_\xi^j(t_2 - p_{\xi,2} - t_1) \\ \text{if } t_1 < t_2 - p_{\xi,2}; \\ f^j(\xi - 1, t_1, t_2) \end{cases}$$

for $\xi = 2, 3, \ldots, n$; $t_1 = p_\xi^j, p_\xi^j + 1, \ldots, d_1$; $t_2 = p_\xi^j + p_{\xi,2}, p_\xi^j + p_{\xi,2} + 1, \ldots, d_2$.

The maximum profit for $P1$ is determined by $Z_C = \max\{f^j(n, t_1, t_2)\}$, where Z_C is the profit of the best selected supplier from $S_j \in H$ and M_2 in the centralised supply chain for $t_1 = p_1^j, p_1^j + 1, \ldots, d_1$; $t_2 = p_1^j + p_{1,2}, p_1^j + p_{1,2} + 1, \ldots, d_2$.

Let A represent the standard machine M_1. Let B represent the expediting machine $S_j \in H$. Let X be the non-integrated warehouse operator. Let Y be the integrated warehouse operator. Let $Z_S^{B,Y}(D_C^*)$ be the solution obtained by Algorithm 1 for the profit of the best selected supplier S with the expediting machine B on $S_j \in H$ and with the integrated warehouse operator Y, where D_C^* is the optimal decision made by the supply chain co-ordinator C. Let $Z_{M_2}^{B,Y}(D_C^*)$ be the solution obtained by Algorithm 1 for the profit of the manufacturer M_2 with expediting machine B on M_2 and with integrated warehouse operator Y. Let $Z_{M_2}^{B,X}(D_C^*)$ be the solution obtained by the variant of Algorithm 1 with replacing α' by α for the profit of the manufacturer M_2 with expediting machine B on M_2 and with non-integrated warehouse operator X. Let $Z_{M_1}^{A,Y}(D_C^*)$ be the solution obtained by the variant of Algorithm 1 with replacing S_j by M_1, p_ξ^j by $p_{\xi,1}$, ϕ^j by ϕ, b_ξ^j by b_ξ and a_ξ^j by a_ξ, where b_ξ is the profit of M_1 excluding the storage costs for $j = 1, 2, \ldots, m$ and $\xi = 1, 2, \ldots, n$ for the profit of M_1 with standard machine A on M_1 and with integrated warehouse operator Y. Let $Z_C^{B,Y}(D_C^*)$ be the profit of the whole supply chain (i.e., $Z_S^{B,Y}(D_C^*) + Z_{M_2}^{B,Y}(D_C^*)$).

Algorithm 2: Maximising the profit in the decentralised supply chain

The solution procedure of Algorithm 2 is similar to that of Algorithm 1 except that the following modifications are required: replace S_j by M_1 and let $b_\xi^j = 0$ in Algorithm 1 because no $S_j's$ profit is considered in $M_2's$ profit function for $j = 1, 2, \ldots, m$ and $\xi = 1, 2, \ldots, n$. Further replace p_ξ^j by $p_{\xi,1}$, ϕ^j by ϕ, α' by α and a_ξ^j by a_ξ for $j = 1, 2, \ldots, m$ and $\xi = 1, 2, \ldots, n$.

Let $Z_{M_2}^{A,X}(D_{M_2}^*)$ be the solution obtained by Algorithm 2 for the profit of M_2, where $D_{M_2}^*$ is the optimal decision made by M_2. Let $Z_{M_1}^{A,X}(D_{M_2}^*)$ be the solution obtained by variant of Algorithm 2 with the equation: total revenue – total cost – $Z_{M_2}^{A,X}(D_{M_2}^*)$ for the profit of M_1.

Since Algorithms 1 and 2 solve $P1$ and $P2$ in pseudo-polynomial time, we have proven that $P1$ and $P2$ are NP-hard in the ordinary sense only.

5. Channel co-ordination

We develop a method (called Ω) for sharing the maximum profit of the whole supply chain by co-ordinating the suppliers, the integrated warehouse operator, and the manufacturer under a contract, where under Ω, we will determine new selling prices of the supplies to achieve co-ordination. The following are the steps for developing Ω:

Step 1: Let Δ be an additional profit gained by the whole supply chain due to the introduction of the expediting machine B and the integrated warehouse operator Y with the optimal decision D_C^* made by the supply chain co-ordinator C with respect to the standard machine A and the non-integrated warehouse operator X with the optimal decision $D_{M_2}^*$ made by the manufacturer M_2. Then we have

$$\Delta = Z_S^{B,Y}(D_C^*) + Z_{M_2}^{B,Y}(D_C^*) - [Z_{M_1}^{A,X}(D_{M_2}^*) + Z_{M_2}^{A,X}(D_{M_2}^*)],$$

or

$$\Delta = Z_C^{B,Y}(D_C^*) - \left[Z_{M_1}^{A,X}(D_{M_2}^*) + Z_{M_2}^{A,X}(D_{M_2}^*)\right].$$

Step 2: Let $P_{M_2}^*$ be an additional profit, which results from $M_2's$ reduced storage costs, contributed by M_2 due to the introduction of B and Y with D_C^* with respect to B and X with D_C^*. Then we have

$$P_{M_2}^* = Z_{M_2}^{B,Y}(D_C^*) - Z_{M_2}^{B,X}(D_C^*).$$

Step 3: Let P_S^* be an additional profit, which results from the increased production rate contributed by the best selected supplier S, due to the introduction of B and Y with D_C^* with respect to A and Y with D_C^*. We thus have

$$P_S^* = Z_S^{B,Y}(D_C^*) - Z_{M_1}^{A,Y}(D_C^*).$$

Step 4: $M_2's$ profit Z_1 with a share of Δ based on its contribution is:

$$Z_1 = Z_{M_2}^{A,X}(D_{M_2}^*) + P_{M_2}^*\Delta/(P_S^* + P_{M_2}^*).$$

Similarly, $S's$ profit Z_2 with a share of Δ based on its contribution is:

$$Z_2 = Z_{M_1}^{A,X}(D_{M_2}^*) + P_S^*\Delta/(P_S^* + P_{M_2}^*).$$

Step 5: Let θ be the sum of the selling prices of the supplies with respect to A and X with $D_{M_2}^*$. Let $J_i \in N'$ be the set of orders with respect to B and Y with D_C^*. Let T_i be each of the sizes of $J_i \in N'$. Let T be the sum of the sizes of $J_i \in N'$. Then the new selling prices θ_i' of $J_i \in N'$ that can be charged to M_2 by S is:

$$\theta_i' = [\theta + P_S^*\Delta/(P_S^* + P_{M_2}^*)](T_i/T).$$

Table 1. Computational times for the problem.

No. of jobs n	100	200	300	400
Mean time t (sec.)	0.22	0.45	0.65	0.88

Theorem 2: *Method Ω provides a profit sharing scheme that ensures that both S and M_2 are better off when the supply chain is co-ordinated.*

Proof of Theorem 2: See Appendix.

As a remark, the above proposed profit sharing co-ordination method can be used to motivate individual supply chain members to work hard together to co-ordinate the supply chain because each member is guaranteed to be better off. Moreover, the division of the supply chain's profit between the members depends on the performance of individual supply chain members. The profit sharing scheme can motivate the members to improve their performance and thus contribute as much as possible to the whole supply chain.

6. Computational experiments

This section presents the computational experiments we conducted to assess the performance of Algorithm 1. All the computer programs were coded in Pascal and were run on a Pentium IV 2.6 GHz/512 MB PC. In the experiments, we consider a supply chain that consists of two suppliers S_1 and S_2, and a manufacturer M_2. Let $d_1 = 9$ months (or 270 days) for the two suppliers and $d_2 = 11$ months (or 330 days) for the manufacturer. Let $\alpha' = 1$ be the rate of the storage cost of the supplies from the two suppliers. Let the production rate of S_1 be $\phi^1 = 30$. Let the production rate of S_2 be $\phi^2 = 20$. Let the range of profits be [\$100,000, \$300,000], the range of proportionate processing times of S_1 be $[10, 20]$ days and the corresponding processing times of the manufacturer be $[30, 60]$, and the range of proportionate processing times of S_2 be $[15, 30]$ corresponding to the same range $[30, 60]$ of M_2, where the data points were obtained from a uniform random number generator. A sample size of 25 for each $n = 100$, 200, 300 and 400 orders was taken. The mean computational time measured in seconds for each sample is shown in Table 1. The computational results show that our algorithm can solve the problem with a reasonably large size very efficiently.

7. Conclusions

This paper is an extension of the single-supplier single-manufacturer two-machine supply chain scheduling problem studied by Yeung *et al.* (2010) to the case with multiple suppliers. We consider both issues of optimal scheduling and supply chain co-ordination. For the decentralised supply chain, we consider that the manufacturer aims to select the orders and maximise its own profit, where there are multiple suppliers, a non-integrated warehouse operator, a single manufacturer, and multiple retailers. The profit function depends on the storage time, storage quantity, order sequence-dependent weighted storage costs, and idle time of the orders. For the centralised supply chain, there exists a supply chain co-ordinator that aims at selecting the orders, maximising the profit of the whole supply chain, and co-ordinating the supply chain members to gain and share the additional benefit. We formulate both sub-problems for the centralised and decentralised supply chains as the two-machine flow shop scheduling problem with common due windows. We develop a theorem and two algorithms to solve these problems. We also develop a method that provides a profit sharing contract, which ensures that both the best selected supplier and manufacturer are better off when the supply chain is co-ordinated. Note that the problem considered in this paper exists in many industries such as in apparel production. For future research, it will be interesting to further extend the problem to consider multiple manufacturers.

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Appendix

Proof of Theorem 1: The quantity of J_i produced on $S_j \in H$ is

$$\phi^j p_i^j = \phi p_i^j / \psi^j, \tag{1}$$

for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$.

Similarly, the same quantity of J_i produced on M_1 is

$$\phi p_{i,1} \tag{2}$$

for $i = 1, 2, \ldots, n$. From (1) and (2), we have

$$p_i^j = p_{i,1}\psi^j \tag{3}$$

for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$.

From (3), we have

$$p_{i,2}/p_i^j = p_{i,2}/(p_{i,1}\psi^j) = \beta/\psi^j \tag{4}$$

for $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$.

Similarly, we have

$$p_{k,2}/p_k^j = p_{k,2}/(p_{k,1}\psi^j) = \beta/\psi^j \tag{5}$$

for $k = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$.

Equating (4) and (5), we have

$$p_{i,2}/p_i^j = p_{k,2}/p_k^j = \beta^j$$

for $i, k = 1, 2, \ldots, n$ $(i \neq k)$ and $j = 1, 2, \ldots, m$.

Thus we prove that β^j is a proportionate constant for the processing time of producing the supplies on $S_j \in H$ and the processing time of producing the products on M_2. □

Proof of Theorem 2: Since $\Delta > 0$, both $Z_1 > Z_{M_2}^{A,X}(D_{M_2}^*)$ and $Z_2 > Z_{M_1}^{A,X}(D_{M_2}^*)$ hold. Thus both S and M_2 are better off. □