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A three-echelon supply chain with price-only contracts and sub-supply chain coordination

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ABSTRACT

This paper studies coordination in a three-echelon supply chain and examines the impact of sub-supply chain coordination (sub-coordination). Our analysis is based on the price-only contracts that are commonly used in practice. The model is of the newsvendor type. We consider the following cases: no coordination between any members of the supply chain (decentralized), coordination between only two members (sub-supply chain coordination) and coordination of the whole supply chain as a benchmark. We explicitly analyze the order quantity and contracting decisions for a decentralized three-echelon supply chain. We compare supply chain efficiency when there is upstream coordination and when there is downstream coordination and show that the former is more efficient than or as efficient as the latter. In our setting, the difference between upstream and downstream sub-supply chain coordination is equivalent to the shortage cost transfer. We find that both the supplier and the retailer would prefer to act alone rather than to coordinate with the manufacturer when sub-supply chain coordination is suggested. This contradiction may partly explain the popularity of price-only contracts in practice.

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1. Introduction

During the last few decades, a rich literature has developed for analyzing the supply chain (SC) coordination issues. Supply chain coordination can be achieved through a centralized decision process or through coordination mechanisms such as supply chain contracts to incentivize decentralized actors to behave coherently with one another. Different models of coordinating contracts have been proposed in the literature. Popular examples include buy-back contracts or return policies (Pasternack, 1985), whereby the supplier allows the buyer to return unsold products at an agreed price; revenue-sharing contracts (Cachon and Lariviere, 2005), whereby the supplier offers a low wholesale price to the retailer, who in turn shares a proportion of his revenue with the supplier; and an innovative inventory policy called consignment stock (Valentini and Zavanella, 2003; Piplani and Viswanathan, 2003), whereby the supplier holds and manages inventories in the retailer's warehouse and the retailer purchases them only at the moment of use. Other contracts are also commonly studied, such as quantity flexibility contracts (Tsay, 1999), quantity discounts

(Weng, 1995), backup agreements (Eppen and Iyer, 1997), sales rebate contracts (Taylor, 2002) and options (Barnes-Schuster et al., 2002). We refer the reader to the comprehensive surveys in Cachon (2003) and Tsay et al. (1999) for more details.

Although supply chain coordination should increase the expected total supply chain profits, in practice, due to accounting and information sharing constraints between the members of a supply chain, coordinating contracts are often difficult to implement. To date, price-only contracts are still popular, even if their use does not lead to coordination of the whole supply chain. Lariviere and Porteus (2001) point out that, "Given the complexity of supply chains, price-only contracts may owe their popularity to their simplicity." Similarly, Cachon (2003) states that, "Even though the wholesale-price contract does not coordinate the supply chain, the wholesale-price contract is worth studying because it is commonly observed in practice."

The majority of the existing literature addresses contract problems in supply chains made up of two echelons. For example, He and Zhang (2008) study a simple supply chain with one supplier and one retailer where there is random yield production and uncertain demand. Jung et al. (2008) propose a negotiation process to find a contract for a distributor and a manufacturer in a supply chain. Wang and Liu (2007) develop a model to study channel coordination and risk sharing in a retailer-led supply chain. Chen (2011) discusses the wholesale price-only contract as

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a benchmark and proposes a returns-discount contract between a manufacturer and a retailer. Some studies on consignment stock policy consider single-supplier single-retailer supply chain by taking into account the risk of obsolescence (Persona et al., 2005), high demand variation coupled with space limitation (Battini et al., 2010a) and learning and forgetting effects (Zanoni et al., 2011). Zavanella and Zanoni (2009) and Battini et al. (2010b) extend to a single-supplier and multi-retailer situation, in which one or more retailers establish a consignment stock policy with the supplier. In practice, however, supply chains typically contain three or more echelons.

In the literature, not many papers have considered multi-echelon supply chains. Munson and Rosenblatt (2001) study the coordination of a three-echelon supply chain with quantity discounts assuming deterministic demand. They consider a multiple-period inventory control model based on the classic economic order quantity (EOQ) model. Jaber et al. (2006) consider price discounts, price-dependent demand, and profit-sharing in a three-echelon supply chain model. Jaber and Goyal (2008) investigate the coordination of order quantities among the players in a three-echelon supply chain with a centralized decision process, allowing for more than one player at each echelon. Jaber et al. (2010) study three-echelon supply chain coordination with learning-based continuous improvement and constant demand. Khouja (2003) and Lee and Moon (2006) likewise assume deterministic demand and employ the EOQ model.

More recent studies consider the coordination of a three-echelon supply chain based on the classic single-period newsvendor model with stochastic demand. Giannoccaro and Pontrandolfo (2004) propose a model with a revenue-sharing contract used by both upstream and downstream supply chain members, which coordinates the three-echelon supply chain. They show that all supply chain actors' profits can be improved by carefully selecting the contract parameters. Ding and Chen (2008) show that a three-echelon supply chain can be fully coordinated with flexible buyback contracts, which allows for all the channel profit to be divided freely among the firms. He and Zhao (2011) study a three-echelon supply chain with both demand and supply uncertainty. They propose an agreement that includes a buyback policy between the manufacturer and the retailer, but stipulates a price-only contract between the supplier and the manufacturer. They show that such an agreement can achieve perfect supply chain coordination and result in a win-win situation.

All of the studies mentioned above explicitly consider a three-echelon supply chain and aim to achieve coordination across the whole supply chain. However, it should be noted that, in practice, many difficulties remain when it comes to implementing such coordination schemes for all supply chain members. For instance, geographical constraints, additional administrative burdens, performance measurement and incentives at individual firms based on a local perspective, dynamically interchanging products, and the like (see Kanda and Deshmukh, 2008) all get in the way of more elaborate coordination mechanisms. It is thus reasonable to expect that coordination of the whole supply chain will be more difficult to achieve than coordination between only some of its members. For example, in the case of a supplier–manufacturer–retailer supply chain, we might expect that coordination between the manufacturer and the retailer would be easier to achieve than coordination among all three parties. Petersen et al. (2005) report that 42% of a sub-sample of companies contacted indicated that “they do not use linked information systems to do planning with their suppliers.” This shows that a non-negligible percentage of firms do not coordinate with their suppliers, and perfect information symmetry is rarely achieved across a multi-echelon supply chain.

In this paper we thus consider a three-echelon (supplier–manufacturer–retailer) supply chain with price-only contracts and

sub-supply chain coordination. The model is of the newsvendor type. The supplier provides raw materials to the manufacturer. The manufacturer sells finished products to the retailer. The demand is random and occurs at the retail level. The retailer sells at a constant selling price that is exogenously determined. We consider the following cases in detail: a decentralized supply chain (no coordination between any members), an upstream-coordinated supply chain (coordination between supplier and manufacturer) and a downstream-coordinated supply chain (coordination between manufacturer and retailer). We also discuss a centralized/coordinated supply chain as a benchmark.

Our study differs from prior work in two major aspects. First, instead of pursuing coordination across the whole supply chain, we study the sub-supply chain coordination problem in a three-echelon supply chain. Second, we explicitly analyze the optimal order quantity for the supplier in a decentralized three-echelon supply chain. With this focus in mind, we begin by investigating the shortage cost transfer effect in a two-echelon supply chain. We then analyze the order quantity and contracting decisions in a decentralized three-echelon supply chain. Finally, we analyze the impact of sub-supply chain coordination on the supplier's optimal order quantity, on the whole supply chain's profit and on the individual firms' profits. We note that in our setting the difference between upstream and downstream sub-supply chain coordination is equivalent to the shortage cost transfer. Using this equivalence, we show that upstream coordination is preferable to downstream coordination. In addition, both the supplier and the retailer would prefer to act alone rather than to coordinate with the manufacturer when sub-supply chain coordination is suggested.

The paper is organized as follows. In Section 2 the basic setting of the model is described. In Section 3 we provide a review of previous results for price-only contracts in a two-echelon supply chain framework. In Section 4 we investigate the shortage cost transfer effect in a two-echelon supply chain. In Section 5 we study a decentralized three-echelon supply chain under price-only contracts. In Section 6 we study the impact of sub-supply chain coordination. We consider two scenarios, upstream and downstream sub-supply chain coordination. In Section 7 we present numerical examples to illustrate our results. In Section 8 we conclude the paper.

2. Assumptions and notations

We consider a three-echelon supply chain composed of a supplier, a manufacturer and a retailer; we assume that all three firms are risk neutral and seek to maximize expected profit. We assume that product demand D follows a continuous distribution with cumulative distribution function (CDF) $F(x)$ and probability distribution function (PDF) $f(x)$. Both $F(x)$ and $f(x)$ are differentiable, and the support of F is $[a, b]$, $0 < a < b \leq \infty$. Let $\bar{F}(x) = 1 - F(x)$ and $\mu = E[D]$. We assume that the lead time for the product is much longer than its selling season. Thus the firms have only one ordering opportunity.

We follow a standard sequence of events as follows. The supplier offers the manufacturer a contract. The manufacturer offers a contract to the retailer. Assuming that all firms accept the contracts, the retailer determines the order quantity q from the manufacturer, and the manufacturer orders the raw materials from the supplier. For simplicity, we assume that a final product requires one raw material. The supplier provides the raw materials. The manufacturer receives the raw materials, produces the products and delivers them to the retailer before the selling season. The demand is realized. Firms are penalized by shortage costs, and transfer payments are made between the coordinated firms according to their contracts. In this paper, we assume that if

two adjacent firms are not coordinated, the upstream firm always serves as the Stackelberg leader (see Cachon, 2003) and the other firm acts as the follower.

We use the following notation.

Decision variables

- q quantity ordered by the retailer
- t wholesale price per unit of raw material determined by the supplier
- w wholesale price per unit of product determined by the manufacturer

Parameters

- p retailer's fixed sale price per unit of final product
- c_s supplier's production cost per unit
- c_m manufacturer's value-added cost per unit
- c_r retailer's treating cost per unit
- g_s supplier's shortage penalty cost per unit of unmet demand
- g_m manufacturer's shortage penalty cost per unit of unmet demand
- g_r retailer's shortage penalty cost per unit of unmet demand
- v salvage revenue (at the retailer) for each unit of the final unsold product
- D nonnegative customer demand, with CDF, $F(x)$ and PDF $f(x)$
- μ mean of customer demand D
- σ standard deviation of customer demand D during the period of interest

In order to avoid trial cases, we make the following assumptions:

Assumption 1. $p > w + c_r, w > t + c_m$, and $t > c_s$.

Assumption 2. $c_s + c_m + c_r > v$.

The first assumption makes sure that each firm is willing to participate. The second assumption ensures that the chain will not produce infinite products.

3. Previous results on price-only contracts

In this section, we briefly revisit the price-only contract that underpins our model, based on the analysis by Cachon (2003) and Lariviere and Porteus (2001). The supply chain is made up of two echelons: a manufacturer and a retailer. In this section, we denote all variables related to the manufacturer and retailer by 2 and 1, respectively.

We assume that $c_2 + c_1 \geq v$, $g_2, g_1 > 0$, $p > c_2 + c_1$. Let $S(q)$ be the expected number of units sold. We recall that

$$S(q) = \int_0^q \bar{F}(x) dx.$$

Then we have the expected inventory after the selling season $E(q-D)^+ = q - S(q)$ and the expected lost sales $E(D-q)^+ = \mu - S(q)$.

As a performance benchmark, the total expected profit of the integrated supply chain for the order quantity q is

$$\hat{\Pi}_T(q) = pS(q) + v(q - S(q)) - g(\mu - S(q)) - cq = (p - v + g)S(q) - (c - v)q - g\mu,$$

where $c = c_2 + c_1$ and $g = g_2 + g_1$. The optimal solution of this concave problem is

$$\bar{F}(q_T^*) = \frac{c - v}{p - v + g}.$$

In the decentralized case under the price-only contract, given the wholesale price w determined by the manufacturer, the retailer's and manufacturer's expected profit functions, which are denoted by $\hat{\pi}_1(q)$ and $\hat{\pi}_2(q)$, respectively, are given by the following equations:

$$\begin{aligned} \hat{\pi}_1(q) &= pS(q) + v(q - S(q)) - g_1(\mu - S(q)) - c_1q - wq \\ &= (p - v + g_1)S(q) - (w + c_1 - v)q - g_1\mu, \\ \hat{\pi}_2(q) &= wq - c_2q - g_2(\mu - S(q)) \\ &= g_2S(q) + (w - c_2)q - g_2\mu. \end{aligned} \tag{1}$$

The retailer's optimal order quantity is

$$\bar{F}(q_1^*) = \frac{w + c_1 - v}{p - v + g_1}.$$

There is a one-for-one mapping between w and q_1^* (Cachon, 2003), and the inverse demand curve for the retailer is

$$w(q) = (p - v + g_1)\bar{F}(q) - (c_1 - v). \tag{2}$$

As the Stackelberg leader, the manufacturer anticipates perfectly the retailer's order quantity for any wholesale price. Facing the inverse demand curve (2), the manufacturer's expected profit function becomes

$$\hat{\pi}_2(q) = g_2S(q) + (p - v + g_1)q\bar{F}(q) - (c - v)q - g_2\mu.$$

Lariviere and Porteus (2001) note that if the manufacturer's marginal profit

$$\frac{\partial}{\partial q} \hat{\pi}_2(q) = \bar{F}(q) \left[(p - v + g) - (p - v + g_1) \frac{qf(q)}{\bar{F}(q)} \right] - (c - v) \tag{3}$$

is decreasing, then $\hat{\pi}_2(q)$ is unimodal, and the optimal manufacturer order quantity satisfies

$$(p - v + g)\bar{F}(q) - (p - v + g_1)qf(q) - (c - v) = 0. \tag{4}$$

The generalized failure rate (GFR) $z(x)$ (Lariviere and Porteus, 2001) of a random variable X with distribution F is

$$z(x) = \frac{xf(x)}{\bar{F}(x)}.$$

An IGFR distribution is a distribution with an increasing GFR. When the distribution of the demand is IGFR we will say interchangeably that the demand is IGFR. Knowing that $\bar{F}(q)$ is decreasing, the manufacturer's marginal profit (3) is decreasing if $qf(q)/\bar{F}(q)$ is increasing.

Let \bar{q} be the largest q for which the following inequality holds:

$$z(q) \leq \frac{p - v + g}{p - v + g_1}.$$

The following result characterizes the optimal manufacturer order quantity in our setting.

Theorem 1. Suppose that the demand is IGFR, then

- (i) $\hat{\pi}_2(q)$ is concave in $[a, \bar{q}]$ and decreasing in $[\bar{q}, \infty)$.
- (ii) Any solution q_2^* of Eq. (4) is unique and must lie in the interval $[a, \bar{q}]$. The manufacturer's optimal order quantity is q_2^* .

Proof. See Lariviere and Porteus (2001) for the proof of their Theorem 1. □

In general, a price-only contract cannot coordinate the supply chain (Cachon, 2003), namely, $\hat{\pi}_2(q_2^*) + \hat{\pi}_1(q_2^*) < \hat{\Pi}_T(q_T^*)$. This is due to the well-known "double marginalization" problem shown by Spengler (1950).

4. Shortage cost transfer

In this section we analyze the effect of shortage cost transfer in a two-echelon supply chain. This effect will be used in our

subsequent analysis of sub-supply chain coordination in Section 6, where we show that the difference between upstream and downstream coordination in a three-echelon supply chain is equivalent to the shortage cost transfer between the members of the supply chain.

Lemma 1. Consider a price-only contract between the members of a two-echelon supply chain. Suppose that the demand is IGFR and that $g = g_1 + g_2$ remains constant when g_1 varies. Then q_2^* decreases when g_1 increases.

Proof. Let us define the following function

$$G(q_2^*, g_1) = \bar{F}(q_2^*)[(p - \nu + g) - (p - \nu + g_1)z(q_2^*)] - (c - \nu).$$

The implicit function $q_2^*(g_1)$ as a function of g_1 is given by the equation $G(q_2^*, g_1) = 0$. Thus

$$\begin{aligned} \frac{\partial q_2^*(g_1)}{\partial g_1} &= - \frac{\frac{\partial G(q_2^*, g_1)}{\partial g_1}}{\frac{\partial G(q_2^*, g_1)}{\partial q_2^*}} \\ &= - \frac{z(q_2^*)}{\frac{f(q_2^*)}{\bar{F}(q_2^*)}[(p - \nu + g) - (p - \nu + g_1)z'(q_2^*)] + (p - \nu + g_1)z''(q_2^*)}, \end{aligned}$$

where $z'(x)$ denotes the first derivative of the function $z(x)$. Then the lemma follows from Theorem 1. □

Note that g is usually considered as a loss-of-goodwill penalty when there is a shortage and demand for the product is realized. This loss of goodwill can frequently be considered constant, given that it depends on the subjective response of the customer in relation to a shortage, and independent of the number of echelons in the supply chain, since usually the final customer is not aware of the supply chain of a product. In some cases, though, the final customer has information on several echelons of the supply chain, which can lead to a “transfer of loss of goodwill” between the members of the supply chain. For example, for well-known brands with high brand recognition, a shortage at a retailer can lead to a loss of goodwill for both the brand and the retailer. By contrast, if the brand recognition of the product is low (e.g., a retailer’s private label product), the customer will perceive that the retailer is not reliable, i.e., most of the loss-of-goodwill penalty will be attributed to the retailer. The brand recognition level will thus determine the shortage cost transfer between the manufacturer and the retailer.

Theorem 2. Consider a price-only contract between the members of a two-echelon supply chain. Suppose that the demand is IGFR and $g = g_1 + g_2$ remains constant when g_1 varies. Then

- (i) $\hat{\pi}_1(q_2^*)$ decreases when g_1 increases.
- (ii) $\hat{\pi}_2(q_2^*)$ increases with g_1 .
- (iii) $\hat{\pi}_1(q_2^*) + \hat{\pi}_2(q_2^*)$ decreases when g_1 increases.

Proof. The retailer’s profit associated with the optimal manufacturer order quantity q_2^* is obtained from Eqs. (1) and (2),

$$\hat{\pi}_1(q_2^*) = (p - \nu + g_1)[S(q_2^*) - q_2^*\bar{F}(q_2^*)] - g_1\mu.$$

We have

$$\frac{\partial \hat{\pi}_1(q_2^*)}{\partial g_1} = \frac{\partial \hat{\pi}_1(q_2^*, g_1)}{\partial g_1} + \frac{\partial \hat{\pi}_1(q_2^*, g_1)}{\partial q_2^*} \frac{\partial q_2^*(g_1)}{\partial g_1}, \quad (5)$$

where we write $\hat{\pi}_1(q_2^*, g_1)$ to express the retailer’s profit as a function of both q_2^* and g_1 .

We consider first the derivative of the retailer’s profit with respect to g_1 without considering the dependence of q_2^* with respect to g_1 .

$$\frac{\partial \hat{\pi}_1(q_2^*, g_1)}{\partial g_1} = -[q_2^*\bar{F}(q_2^*) + (\mu - S(q_2^*))]. \quad (6)$$

Eq. (6) proves (i) for the case when q_2^* is constant as a function of g_1 .

Next, we consider the variation in profit due to the dependence of the optimal order quantity q_2^* on g_1 . We first consider the derivative of the retailer’s profit with respect to q_2^* .

$$\frac{\partial \hat{\pi}_1(q_2^*, g_1)}{\partial q_2^*} = (p - \nu + g_1)q_2^*f(q_2^*).$$

Then from Eq. (5) and Lemma 1 the following inequality is obtained:

$$\frac{\partial \hat{\pi}_1(q_2^*)}{\partial g_1} \leq 0,$$

and we have demonstrated (i).

For the manufacturer’s profit we have

$$\frac{\partial \hat{\pi}_2(q_2^*)}{\partial g_1} = \frac{\partial \hat{\pi}_2(q_2^*, g_1)}{\partial g_1} + \frac{\partial \hat{\pi}_2(q_2^*, g_1)}{\partial q_2^*} \frac{\partial q_2^*(g_1)}{\partial g_1}.$$

But the first-order condition (FOC) for q_2^* guarantees that

$$\frac{\partial \hat{\pi}_2(q_2^*, g_1)}{\partial q_2^*} = 0.$$

Then

$$\frac{\partial \hat{\pi}_2(q_2^*)}{\partial g_1} = \frac{\partial \hat{\pi}_2(q_2^*, g_1)}{\partial g_1} = q_2^*\bar{F}(q_2^*) + (\mu - S(q_2^*)).$$

Therefore (ii) and (iii) follow. □

In a two-echelon supply chain with a price-only contract, Theorem 2 shows first that the efficiency of the supply chain (the ratio of supply chain profit to the centralized optimal profit) decreases when the retailer’s shortage cost g_1 increases. From Lemma 1 we see that the manufacturer’s optimal order quantity decreases when g_1 increases. In accordance with the concavity of the profit of the whole supply chain, we can also expect the supply chain’s efficiency to decrease when g_1 increases. Second, Theorem 2 indicates that the profit share of the upstream firm (the manufacturer) increases when the shortage cost is transferred to the downstream firm (the retailer) by increasing g_1 , and at the same time, the profit of downstream firm decreases.

The results in this section show that under a price-only contract model with the manufacturer as the leader, it is not favorable for the whole supply chain if the retailer’s shortage penalty is increased. However, the manufacturer could benefit from this shortage penalty transfer.

In the context of our prior reference to relative brand recognition, the split of the shortage penalty between a manufacturer and a retailer can be understood as follows: Suppose that the manufacturer sells a well-known, high quality brand. She will be interested in avoiding high shortage penalties for the retailer when it comes to optimizing the whole supply chain, because in this way customers will be more likely to revisit the store. When it comes to maximizing her own profit, the situation changes. The manufacturer will be interested in transferring most of the shortage penalty to the retailer. As the retailer will

order less, the manufacturer can sell more via other channels if the manufacturer enjoys strong brand recognition for its product in retail.

5. A three-echelon decentralized supply chain

In this section we consider a three-echelon decentralized supply chain with profit-maximizing supplier, manufacturer and retailer. Both supplier and manufacturer offer price-only contracts to their downstream firm.

Given the wholesale prices determined by the supplier and the manufacturer, the profits for each member of the supply chain become

$$\pi_r(q) = (p - v + g_r)S(q) - (w + c_r - v)q - g_r\mu,$$

$$\pi_m(q) = g_m S(q) + (w - c_m - t)q - g_m\mu,$$

$$\pi_s(q) = g_s S(q) + (t - c_s)q - g_s\mu.$$

As a benchmark, let us consider the total expected profit of the coordinated supply chain for order quantity q given by

$$\Pi_T(q) = \pi_r + \pi_m + \pi_s = (p - v + g)S(q) - (c - v)q - g\mu,$$

where $c = c_s + c_m + c_r$ and $g = g_s + g_m + g_r$. The optimal order quantity q^* for the coordinated supply chain satisfies

$$(p - v + g)\bar{F}(q^*) = c - v.$$

As in Section 3, given the retailer's inverse demand Eq. (7),

$$w(q) = (p - v + g_r)\bar{F}(q) - (c_r - v), \tag{7}$$

the profit for the manufacturer, anticipating the optimal response of the retailer, is

$$\pi_m(q) = g_m S(q) + (p - v + g_r)q\bar{F}(q) - (c_m + c_r - v + t)q - g_m\mu.$$

We have

$$\frac{\partial}{\partial q} \pi_m(q) = (p - v + g_m + g_r)\bar{F}(q) - (p - v + g_r)qf(q) - (c_m + c_r - v + t).$$

Then the inverse demand curve for the manufacturer is

$$t(q) = (p - v + g_m + g_r)\bar{F}(q) - (p - v + g_r)qf(q) - (c_m + c_r - v). \tag{8}$$

The profit for the supplier, anticipating the optimal response of the manufacturer, is

$$\pi_s(q) = g_s S(q) + (p - v + g_m + g_r)q\bar{F}(q) - (p - v + g_r)q^2 f(q) - (c - v)q - g_s\mu.$$

And the supplier's marginal profit is

$$\begin{aligned} \frac{\partial}{\partial q} \pi_s(q) &= (p - v + g)\bar{F}(q) - (p - v + g_m + g_r)qf(q) \\ &\quad - (p - v + g_r)[2qf(q) + q^2 f'(q)] - (c - v) \\ &= (p - v + g)\bar{F}(q) - g_m qf(q) \\ &\quad - (p - v + g_r)[3qf(q) + q^2 f'(q)] - (c - v). \end{aligned}$$

In the text that follows, we analyze the characteristics of the supplier's optimal order quantity in a decentralized three-echelon supply chain.

Theorem 3. Suppose that

1. F is IGFR.
2. $3z(q) + q^2 f'(q) / \bar{F}(q)$ increases with q .

Then: (i) $\pi_s(q)$ is concave in $[a, \bar{q}_s]$ and decreasing in $[\bar{q}_s, \infty)$, where \bar{q}_s is the greatest $q \geq 0$ for which the following inequality holds:

$$(p - v + g) \geq g_m z(q) + (p - v + g_r) \left(3z(q) + q^2 \frac{f'(q)}{\bar{F}(q)} \right).$$

(ii) Any solution q_s^* of Eq. (9) is unique and must lie in the interval $[a, \bar{q}_s]$. The supplier's optimal order quantity is q_s^* .

$$(p - v + g)\bar{F}(q) - g_m qf(q) - (p - v + g_r)[3qf(q) + q^2 f'(q)] = (c - v). \tag{9}$$

Proof. Let us write Eq. (9) in the following way.

$$\bar{F}(q) \left[(p - v + g) - g_m \frac{qf(q)}{\bar{F}(q)} - (p - v + g_r) \left(3 \frac{qf(q)}{\bar{F}(q)} + q^2 \frac{f'(q)}{\bar{F}(q)} \right) \right] = (c - v). \tag{10}$$

Because of Conditions 1 and 2 in Theorem 3, the left-hand side (LHS) of Eq. (10) is positive and decreasing in the interval $[a, \bar{q}_s]$. Then the supplier's marginal profit $(\partial/\partial q)\pi_s(q)$ is positive and decreasing. The supplier's profit $\pi_s(q)$ is concave in this interval. $(\partial/\partial q)\pi_s(q)$ is negative in the interval $[\bar{q}_s, \infty)$ then $\pi_s(q)$ decreases. This proves the result (i). $\pi_s(q)$ is concave in $[a, \bar{q}_s]$ and decreases in $[\bar{q}_s, \infty)$. Then (ii) follows. \square

The supplier's problem in a three-echelon supply chain with price-only contracts (Eq. (9)) is less easy to analyze than the manufacturer's problem in a two-echelon supply chain with price-only contracts. However, we find that Condition 2 in Theorem 3 holds for some commonly utilized demand distributions (Cachon, 2003), such as uniform distribution, normal distribution in the interval $[0 \leq q \leq \mu/2]$, exponential distribution (Larivière and Porteus, 1999) in the interval $[0 \leq q \leq 3\mu/2]$ and power function $\Phi(x) = (x/\theta)^k$, $0 \leq x \leq \theta$, $k \geq 0$.

In this section, we explicitly analyzed on the optimal order quantity of the supplier, who serves as the Stackelberg leader in a decentralized three-echelon supply chain. We also studied the implicit contracting decisions and the expected profits of the supply chain members.

6. Sub-supply chain coordination

We now consider the case in which coordination is achieved between only two members of the supply chain. The cost contributions (shortage and production costs) of the sub-supply chain are calculated as the sum of the costs of its two members (e.g., the shortage cost for the coordinated manufacturer-retailer sub-supply chain becomes $g_m + g_r$).

Consider that the retailer and the manufacturer are coordinated with a total profit $\hat{\pi}_{mr}$. This coordination could be achieved simply by having a single decision maker who decides the order quantity for both firms, or by a coordinating contract such as a buyback or a revenue-sharing contract. In this supply chain, the supplier acts as the Stackelberg leader and the coordinated manufacturer-retailer acts as the follower. The profits associated with these two players are the following:

$$\hat{\pi}_s = g_s S(q) - c_s q - g_s \mu + tq. \tag{121}$$

$$\hat{\pi}_{mr} = (p - v + g_m + g_r)S(q) - (c_m + c_r - v)q - (g_m + g_r)\mu - tq. \tag{123}$$

Remark 1. Note that $\hat{\pi}_{mr}$ and $\hat{\pi}_s$ are written as $\hat{\pi}_1$ and $\hat{\pi}_2$, respectively, in Eq. (1), with $g_1 = g_m + g_r$, $g_2 = g_s$, $c_1 = c_m + c_r$ and $c_2 = c_s$.

Consider now that the supplier and the manufacturer are coordinated. As for the downstream coordination mentioned above, the upstream coordination could be achieved simply by having a common decision maker, or by a coordinating contract such as a revenue-sharing contract. In this case, the coordinated supplier-manufacturer acts as the leader and the retailer acts as

the follower. The profits associated with these two players are

$$\hat{\pi}_{sm} = (g_s + g_m)S(q) - (c_s + c_m)q - (g_s + g_m)\mu + wq$$

$$\hat{\pi}_r = (p - \nu + g_r)S(q) - (c_r - \nu)q - g_r\mu - wq.$$

Remark 2. Note that $\hat{\pi}_r$ and $\hat{\pi}_{sm}$ are written as $\hat{\pi}_1$ and $\hat{\pi}_2$, respectively, in Eq. (1), with $g_1 = g_r$, $g_2 = g_s + g_m$, $c_1 = c_r$ and $c_2 = c_m + c_s$.

From Remarks 1 and 2, we can see that a three-echelon supply chain including one firm acting alone with the other two being coordinated, can be considered as a two-echelon supply chain.

We denote the wholesale price determined by the leader in the downstream-(upstream-)coordinated supply chain by $t_{s,mr}$ ($w_{sm,r}$). From Eq. (2) we obtain the following result:

$$\left| \frac{\partial}{\partial q} t_{s,mr}(q) \right| \geq \left| \frac{\partial}{\partial q} w_{sm,r}(q) \right|.$$

That is, when there is coordination downstream the wholesale price is more sensitive to the decision variable for a given value of q .

6.1. Impact on the supplier's optimal order quantity and the whole chain's profit

In this section we compare the Stackelberg leader's optimal order quantity and the whole supply chain's profit for the two types of sub-supply chain coordination mentioned above and the decentralized supply chain.

Theorem 4. Suppose that F is IGFR. We denote the optimal order quantity for the leader in an upstream-coordinated and a downstream-coordinated supply chain by $q_{sm,r}^*$ and $q_{s,mr}^*$, respectively. Then we have $q_{sm,r}^* \geq q_{s,mr}^*$.

Proof. The result follows from Lemma 1, and Remarks 1 and 2. □

We denote the whole profit associated with the Stackelberg leader's optimal order quantity for an upstream-coordinated and a downstream-coordinated supply chain by $\Pi_{sm,r}(q_{sm,r}^*)$ and $\Pi_{s,mr}(q_{s,mr}^*)$, respectively. Because of the concavity of the supply chain profit we obtain the following corollary from Theorem 4.

Corollary 1. Under the same conditions of Theorem 4 we obtain that

$$\Pi_{sm,r}(q_{sm,r}^*) \geq \Pi_{s,mr}(q_{s,mr}^*).$$

This indicates that the efficiency of the upstream-coordinated supply chain is greater than or equal to the efficiency of the downstream-coordinated supply chain. From the point of view of the whole supply chain's profit, it is better to coordinate the upstream firms than the downstream ones.

Theorem 5. Suppose that the following conditions hold:

1. F is IGFR.
2. $2f(q)/\bar{F}(q) + qf'(q)/\bar{F}(q) \geq 0$.

We denote the optimal order quantity for the supplier in the decentralized supply chain by $q_{s,m,r}^*$, then we have $q_{s,mr}^* \geq q_{s,m,r}^*$.

Proof. The optimal order quantity for the supplier in the downstream-coordinated supply chain $q_{s,mr}^*$ is the solution

of Eq. (11).

$$(p - \nu + g)\bar{F}(q) - (p - \nu + g_m + g_r)qf(q) = (c - \nu). \tag{11}$$

And $q_{s,m,r}^*$ is a solution of Eq. (12), which is equivalent to Eq. (9).

$$(p - \nu + g)\bar{F}(q) - (p - \nu + g_m + g_r)qf(q) - (p - \nu + g_r)[2qf(q) + q^2f'(q)] = (c - \nu). \tag{12}$$

Then the result follows from the ordering of the LHS of Eqs. (12) and (11). □

As for Condition 2 in Theorem 3, Condition 2 in Theorem 5 holds for some commonly used demand distributions, e.g., uniform distribution, normal distribution in the interval $[0 \leq q \leq \mu/2 + \sqrt{2\sigma^2 + \mu^2}/4]$, exponential distribution in the interval $[0 \leq q \leq 2\mu]$ and power function $\Phi(x) = (x/\theta)^k$, $0 \leq x \leq \theta$, $k \geq 0$.

We denote the whole profit for the decentralized supply chain associated with the supplier's optimal order quantity by $\Pi_{s,m,r}(q_{s,m,r}^*)$. Because of the concavity of the whole supply chain profit, we obtain the following corollary from Theorem 5.

Corollary 2. Under the same conditions of Theorem 5 we obtain that

$$\Pi_{s,mr}(q_{s,mr}^*) \geq \Pi_{s,m,r}(q_{s,m,r}^*).$$

The efficiency of the downstream-coordinated supply chain is greater than or equal to the efficiency of the decentralized supply chain. This indicates that the double marginalization is partly mitigated by coordination between a subset of supply chain members.

6.2. Impact on individual firms' profit

Next we analyze the impact of sub-supply chain coordination on individual firms' profit, especially the profits of the supplier and the retailer who could act alone in such a supply chain.

Theorem 6. Suppose that the demand is IGFR. Then

- (i) $\hat{\pi}_{s;s,mr}(q_{s,mr}^*) \geq \hat{\pi}_{sm;sm,r}(q_{sm,r}^*)$, where $\hat{\pi}_{s;s,mr}$ is the supplier's profit in the downstream-coordinated supply chain (s,mr) and $\hat{\pi}_{sm;sm,r}$ is the sum of the profits of the supplier and the manufacturer in the upstream-coordinated supply chain (sm,r).
- (ii) $\hat{\pi}_{r;sm,r}(q_{sm,r}^*) \geq \hat{\pi}_{mr;s,mr}(q_{s,mr}^*)$, where $\hat{\pi}_{r;sm,r}$ is the retailer's profit in the upstream-coordinated supply chain (sm,r) and $\hat{\pi}_{mr;s,mr}$ is the sum of the profits of the manufacturer and the retailer in the downstream-coordinated supply chain (s,mr).

Proof. The result (i) follows from Remarks 1 and 2 and Theorem 2. Recall that in Corollary 1 we have $\Pi_{sm,r}(q_{sm,r}^*) \geq \Pi_{s,mr}(q_{s,mr}^*)$. Because of the result (i), it is straightforward that $\hat{\pi}_{r;sm,r}(q_{sm,r}^*) \geq \hat{\pi}_{mr;s,mr}(q_{s,mr}^*)$. □

The supplier's share of the profit in the s,mr supply chain is greater than or equal to the share of the profit of the coordinated supplier–manufacturer in the sm,r supply chain. Consequently, the supplier will be more interested in acting alone in a three-echelon supply chain with sub-coordination, because she earns more profit than the total profit when she coordinates with the manufacturer.

Similarly, the retailer prefers to act alone in a three-echelon supply chain with sub-coordination. Since the manufacturer's profit in a supply chain with sub-coordination depends on the manufacturer's bargaining power in terms of sub-supply chain profit allocation, comparing the manufacturer's profit between upstream and downstream sub-coordination is not straightforward.

In this section, we compared two types of sub-supply chain coordination: upstream and downstream. Our analysis shows that the leader's optimal quantity and consequently the supply chain's efficiency is higher when there is upstream coordination than when there is downstream coordination. From the point of view of the whole supply chain, it is better to coordinate upstream firms. However, from the point of view of individual firms' profit, both the supplier and the retailer would prefer to act alone rather than to coordinate with the manufacturer when sub-supply chain coordination is suggested.

7. Numerical studies

This section illustrates our results with numerical analysis. We adopt the price and cost parameter setting of Ding and Chen (2008) and He and Zhao (2011) as follows: $p=150, v=15, c=60, g=12$. The demand is assumed to follow a uniform distribution with mean $\mu=1000$ and support $[0, 2000]$. In Section 7.1 we first demonstrate the shortage cost transfer effect in a two-echelon supply chain. In Section 7.2 we focus on supply chains that include three echelons.

7.1. Two-echelon shortage cost transfer effect

First we consider a two-echelon supply chain with a price-only contract between the manufacturer and the retailer. Let $c_1=20, c_2=40, g$ is constant and g_1 varies. We analyze the impact of the shortage cost transfer on the manufacturer's optimal order quantity, on the associated profits of each echelon and on the whole supply chain. Fig. 1 shows that the manufacturer's optimal order quantity decreases when g_1 increases. This follows the result in Lemma 1.

As discussed in Theorem 2, Fig. 2 shows that when g_1 increases, the manufacturer's profit also increases, whereas the profits of both the retailer and the whole supply chain decrease. It is worth noting that when the retailer takes responsibility for the major part of a non-negligible shortage penalty g , she may end with a negative profit. This is not acceptable when it comes to establishing a contract.

7.2. Three-echelon supply chain

In this section, we compare four types of supply chain: decentralized (s, m, r), downstream-coordinated (s, mr), upstream-coordinated (sm, r) and centralized. We set $c_r=5, c_m=15$ and $c_s=40$.

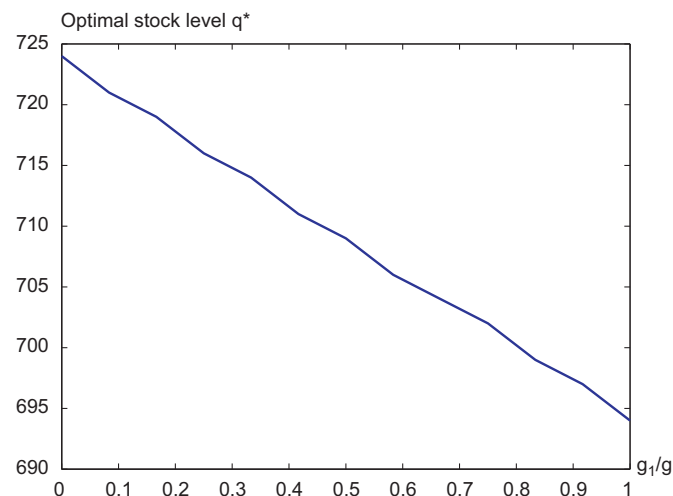


Fig. 1. Impact of shortage cost transfer on manufacturer's optimal order quantity.

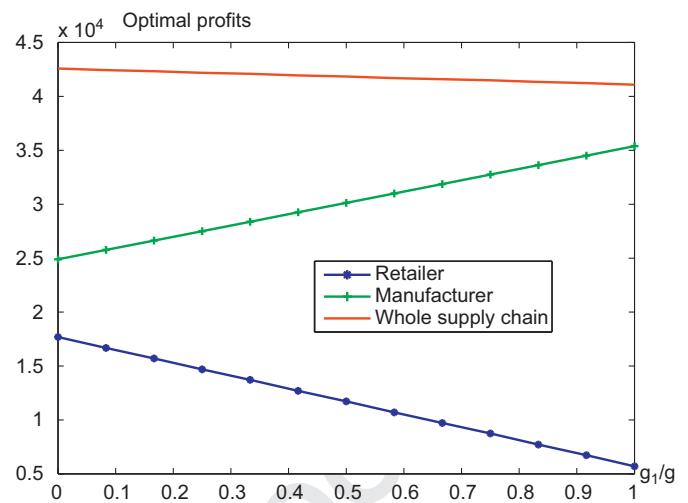


Fig. 2. Impact of shortage cost transfer on profit.

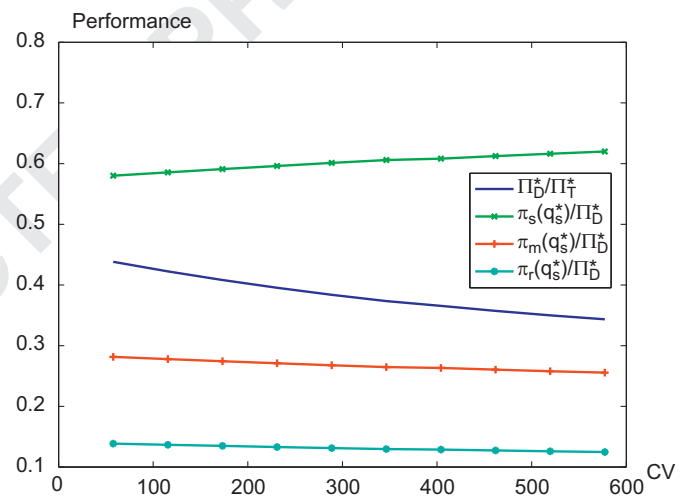


Fig. 3. Impact of coefficient of variation on supply chain member performance.

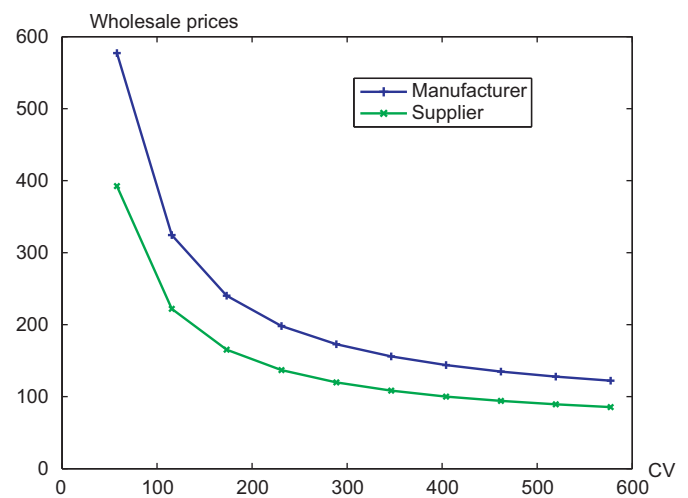


Fig. 4. Impact of coefficient of variation on wholesale prices.

For the decentralized case, the supplier is the Stackelberg leader of the whole supply chain. Numerical results show that the supplier tends to allocate the majority of the whole supply chain's profit to herself, by setting a relatively high sales price. If

Table 1
Decisions and expected profits of firms with $g_s = 6, g_m = 4, g_r = 2$.

Supply chain	q^*	Π^*	π_s	π_m	π_r	Wholesale price
Decentralized	363	20 185	12 513	5158	2514	t: 86 w: 122
Downstream-coordinated	709	41 846	30 125	$\pi_{mr} =$	11 721	86
Upstream-coordinated	719	42 341	$\pi_{sm} =$	26 634	15 707	98
Centralized	1388	58 776	–	–	–	–

the retailer's shortage penalty is relatively high, then the supplier's optimal solution may lead to a negative profit for the retailer. In order to make sure each firm is willing to participate, we consider that the shortage penalty is allocated in the following way: $g_s = 6, g_m = 4, g_r = 2$. Fig. 3 shows that the efficiency of the decentralized supply chain (Π_D^*/Π_r^* , with $\Pi_D^* = \pi_s(q_s^*) + \pi_m(q_m^*) + \pi_r(q_r^*)$) falls when the coefficient of variation (CV) of the demand increases. Concerning individual firms' profit in our example, an increase in demand uncertainty increases the profit ratio of the supplier ($\pi_s(q_s^*)/\Pi_D^*$), but slightly decreases that of the manufacturer and the retailer. The wholesale prices determined by both the supplier and the manufacturer, calculated by Eqs. (7) and (8), decrease with demand uncertainty (as shown in Fig. 4).

Table 1 displays for each type of supply chain considered, the leader's optimal order quantity q^* , the associated profit of the whole supply chain Π^* , the profit of each firm (π_s, π_m and π_r), and the wholesale prices determined by the leader. For the coordinated members of the sub-supply chains, we give the sum of their profits instead of individual ones.

The centralized supply chain is naturally the most efficient of the four supply chain types. It has the highest order quantity and makes the largest profit. It is hardly surprising that the decentralized supply chain has the lowest order quantity and the worst performance. Note that in the type of supply chain where the upstream firm acts as leader and where the retailer has little bargaining power, the retailer earns relatively small profits.

As analyzed in Section 6, Table 1 shows that an upstream-coordinated supply chain outperforms a downstream-coordinated one. Moreover, both the supplier and the retailer would earn higher profits by acting alone rather than coordinating with the manufacturer when sub-supply chain coordination is suggested.

The example in Table 1 also shows that, compared with a decentralized supply chain, both the supplier and the retailer may still prefer to join in a supply chain with sub-coordination even if they have to coordinate with the manufacturer. This is because that in a three-echelon supply chain with sub-coordination, it may be possible to structure a win-win situation for all supply chain members because the total profit $\hat{\pi}_{mr}$ in the downstream-coordinated supply chain exceeds $\pi_m + \pi_r$ in the decentralized supply chain, and $\hat{\pi}_{sm}$ in the upstream-coordinated supply chain exceeds $\pi_s + \pi_m$ in the decentralized supply chain (Table 1).

8. Conclusion

This paper considers a three-echelon supply chain with random demand. We examined the following cases: a decentralized supply chain, upstream coordination, downstream coordination and a centralized/coordinated supply chain. Using price-only contracts, it is not as easy to study order quantity and contracting decisions in a decentralized three-echelon supply chain as it is in a two-echelon supply chain. We analyze the shortage cost transfer effect in a two-echelon supply chain and show that in our setting, the difference between upstream and downstream coordination is equivalent to the shortage cost transfer. From the point of view of the whole supply chain, it is

more profitable to coordinate between the supplier and the manufacturer than between the manufacturer and the retailer. Moreover, our analysis shows that both the supplier and the retailer would prefer to act alone rather than to coordinate with the manufacturer when sub-supply chain coordination is suggested. This contradiction may partly explain the popularity of price-only contracts in practice.

The analysis in this paper can be extended in several directions. First, we assume in this paper that the retail price p is exogenously given. In reality, some retailers jointly determine the retail price and order quantity. With the ability to determine the retail price, the retailer's profit in a decentralized supply chain may be improved. Second, the supply chain may contain more than one firm in each echelon. The competition between firms in each echelon might induce the supplier to produce more and the retailer to order more, as discussed in He and Zhao (2011). It would be interesting to investigate how this competition influences the order quantity and contracting decisions in our setting.

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