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Sub-Coordination in a Competing Supply Chain With a 3PL Provider

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ABSTRACT Coordinating contracts are sometimes difficult to be established because of information sharing constraints and additional administrative burdens. Considering the difficulties of coordinating contracts, it is reasonable that coordination between only some of chain members will be easier to achieve than coordination of the whole supply chain. For convenience, coordination between only some of chain members is referred to sub-coordination. This paper discusses three types of sub-coordination in a competing supply chain comprising two manufacturers, a retailer, and a 3PL provider. Using the fully decentralized supply chain as a benchmark, the effects of sub-coordination on the supply chain are investigated. We find out that sub-coordination is not always effective to improve the profit of the supply chain, in some cases sub-coordination even does harm to supply chain members or the whole supply chain. The performance of sub-coordination critically depends on the degree of product substitutability.

INDEX TERMS Competing supply chain, 3PL provider, sub-coordination.

I. INTRODUCTION

A supply chain is a complex network comprising multiple members. The contradiction of different objectives always leads to the loss of the profits, therefore, the channel coordination mechanisms are used to improve the supply chain performance. Different coordinating contracts have been proposed in the literature, including buy-back contracts [1]–[3], quantity discount contracts [4]–[7], quantity flexibility contracts [8]–[11], and revenue-sharing contracts [12]–[16]. Although coordinating contracts can increase the profit of the whole supply chain, however, coordinating contracts are sometimes difficult to be established due to information sharing constraints and additional administrative burdens. For example, Cachon and Lariviere pointed out the limitations of using revenue-sharing contracts. They identified three limitations that prevent revenue sharing emerging in every industry, and one of the most significant limitations is the administrative burden. Under revenue sharing, the supplier must monitor the revenues of retailer to verify that they are split appropriately [17]. Considering the difficulties of coordinating contracts, it is reasonable that coordination between only some of chain members will be easier to achieve than coordination of the whole supply chain. For convenience, coordination between only some of chain members is referred to sub-coordination. Seifert explained sub-coordination in detail and pointed out the importance of sub-coordination to the supply chain [18]. Different from the study of Seifert, we discuss sub-coordination in a competing supply chain with a 3PL provider

Most of the existing literature addresses coordination problems in a supply chain without a 3PL provider [19]–[22]. However, in reality, many firms use the logistics service of the 3PL provider, and the 3PL provider plays a key role in managing the whole supply chain [23]. The study on the 3PL provider is evolving rapidly [24]–[29]. It should be noted that the price of the 3PL provider will cause well known double marginalization, which destroys the profit of the whole supply chain. It is better that supply chain coordination should involve the 3PL provider. In order to mitigate double marginalization caused by the 3PL provider, some coordination contracts could be used.

Our work is also related to previous research on the competing supply chain. There are many substitutable products

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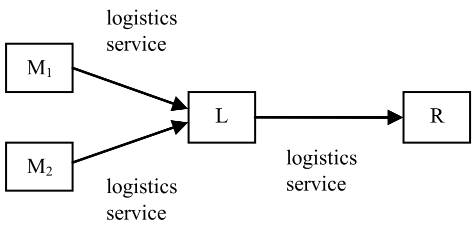

FIGURE 1. A competing supply chain comprising two manufacturers, a 3PL provider, and a retailer.

in market, for example, Dell and HP in computer market, GM and Ford in auto industry. In recent years, the competing channel structure has been of growing interest to academicians [30]–[33]. This paper considers a competing supply chain (see Fig.1) comprising two manufacturers (denoted by M_1 and M_2), a 3PL provider (denoted by L), and a retailer (denoted by R). Each manufacturer produces only one product, which is a substitute for the other manufacturer's product. The two manufacturers sell the substitutable products to the common retailer through the logistics service of the 3PL provider.

In this paper, the optimal decision of the fully decentralized system is first characterized and it is used as a benchmark to evaluate the performance of sub-coordination. Furthermore, we discuss three types of sub-coordination. The first one is the coordination only between the retailer and the 3PL provider, simplified by R-L coordination. The second one is the coordination only between the manufacturers and the 3PL provider, simplified by M-L coordination. The third one is the coordination only between the manufacturers and the retailer, simplified by M-R coordination. The sub-coordination mentioned above could be achieved by a coordinating contract, or by having a single decision maker who owns all the decision powers. Two main questions are raised in this paper:

(1) How sub-coordination affects the performance of the supply chain, and under what conditions some of them are willing to form sub-coordination.
(2) How competition between the two manufacturers affects the performance of sub-coordination, whether the performance of sub-coordination depends on the degree of product substitutability.

Our main contributions are as below. (1) We combine the competing supply chain with the 3PL provider, and propose a generalization of previous models and approaches. (2) Considering the difficulties of coordinating contracts for all members, we devise three types of sub-coordination which are easier to achieve than coordination of the whole supply chain. The efficiency of sub-coordination is discussed.

II. THE MODEL

Following previous literature [34]–[40], we assume that the demand of product i is decreasing in its own retail price and increasing in that of the competitor. The demand function is given by

$$q_i = Q_0 - \alpha p_i + \beta p_j, \quad i = 1, 2 \text{ and } j = 3 - i \tag{1}$$

where p_i denotes the product i's retail price, Q_0 ($Q_0 > 0$) denotes the demand when the prices of two products are zero, $\alpha(\alpha > 0)$ denotes the parameter that influences consumer sensitivity to retail price, and $\beta(\beta > 0)$ denotes the sensitivity of product i 's sale to change in product j's retail price. We assume $\alpha > \beta$, which is reasonable because the demand for product is more sensitive to its own retail price than that of the competitor. Inhere α and β capture the product differentiation, and $\rho = \beta/\alpha$ is related to the degree of product substitutability, that is, the greater β/α, the more substitutable it is.

c_M denotes the manufacturer's unit manufacturing cost. Following previous literature, we assume that the manufacturing costs of two manufacturers are the same. c_L denotes the 3PL provider's unit operational cost. c_R denotes the retailer's unit retail cost. We let $c = c_M + c_L + c_R$. The decision variable w_i denotes the product i's wholesale price charged by manufacturer i to the retailer. The decision variable m denotes the logistics service price charged by the 3PL provider to the retailer. All data is assumed to be common knowledge.

III. THE FULLY DECENTRALIZED SUPPLY CHAIN

The sequence of events taking place within the decentralized system is as follows. (1) The manufacturer i determines the wholesale price w_i to the retailer. (2) The 3PL provider offers logistics service price m to the retailer. (3) The retailer determines retail prices p_1 and p_2 to the customers. Manufacturer 1's profit function $\prod_{M1}$, manufacturer 2's profit function $\prod_{M2}$, the 3PL provider's profit function $\prod_L$, and the retailer's profit function $\prod_R$ can be expressed as

$$\prod\nolimits_{M1} = (w_1 - c_M)(Q_0 - \alpha p_1 + \beta p_2) \tag{2}$$

$$\prod\nolimits_{M2} = (w_2 - c_M)(Q_0 - \alpha p_2 + \beta p_1) \tag{3}$$

$$\prod\nolimits_{L} = \sum_{i=1}^{2} (m - c_L)(Q_0 - \alpha p_i + \beta p_j) \tag{4}$$

$$\prod\nolimits_{R} = \sum_{i=1}^{2} (p_i - w_i - m - c_R)(Q_0 - \alpha p_i + \beta p_j) \tag{5}$$

The profit function of the whole supply chain is

$$\begin{aligned}\prod\nolimits_{T} &= \prod\nolimits_{M1} + \prod\nolimits_{M2} + \prod\nolimits_{L} + \prod\nolimits_{R} \\ &= \sum_{i=1}^{2} (p_i - c)(Q_0 - \alpha p_i + \beta p_j)\end{aligned} \tag{6}$$

The model is solved through backwards induction. Given w_1, w_2 and m, the retailer determines p_1 and p_2 to maximize its profit as given in (5). According to the first-order conditions $\partial \prod_R / \partial p_1 = 0$, $\partial \prod_R / \partial p_2 = 0$, the best reaction functions of the retailer are

$$\begin{aligned} p_1 &= \frac{Q_0 + (\alpha - \beta)(w_1 + m + c_R)}{2(\alpha - \beta)} \\ p_2 &= \frac{Q_0 + (\alpha - \beta)(w_2 + m + c_R)}{2(\alpha - \beta)} \end{aligned} \tag{7}$$

TABLE 1. Optimal solutions in the decentralized supply chain.

Optimal prices	Optimal profits
M₁: $w_1^* = \frac{2Q_0 - 2(\alpha-\beta)(c_R+c_L)+(3\alpha+\beta)c_M}{5\alpha-\beta}$	$\prod_{M1}^* = \frac{3\alpha+\beta}{2(5\alpha-\beta)^2}[Q_0-(\alpha-\beta)c]^2$
M₂: $w_2^* = \frac{2Q_0 - 2(\alpha-\beta)(c_R+c_L)+(3\alpha+\beta)c_M}{5\alpha-\beta}$	$\prod_{M2}^* = \frac{3\alpha+\beta}{2(5\alpha-\beta)^2}[Q_0-(\alpha-\beta)c]^2$
3PL: $m^* = \frac{(3\alpha+\beta)Q_0}{2(\alpha-\beta)(5\alpha-\beta)} - \frac{(3\alpha+\beta)(c_R+c_M)-(7\alpha-3\beta)c_L}{2(5\alpha-\beta)}$	$\prod_L^* = \frac{(3\alpha+\beta)^2}{4(\alpha-\beta)(5\alpha-\beta)^2}[Q_0-(\alpha-\beta)c]^2$
R: $p_1^* = p_2^* = \frac{(17\alpha-5\beta)Q_0}{4(\alpha-\beta)(5\alpha-\beta)} + \frac{(3\alpha+\beta)c}{4(5\alpha-\beta)}$	$\prod_R^* = \frac{(3\alpha+\beta)^2}{8(\alpha-\beta)(5\alpha-\beta)^2}[Q_0-(\alpha-\beta)c]^2$
the supply chain: N/A	$\prod_T^* = \frac{(3\alpha+\beta)(17\alpha-5\beta)}{8(\alpha-\beta)(5\alpha-\beta)^2}[Q_0-(\alpha-\beta)c]^2$

Given w_1 and w_2, the 3PL provider determines m to maximize its profit as given in (4). Substituting (7) into (4), and applying the first-order condition $\partial \prod_L / \partial m = 0$ to the resulting profit function, the best reaction function of the 3PL provider is

$$m = \frac{2Q_0 - (\alpha-\beta)(w_1+w_2+2c_R-2c_L)}{4(\alpha-\beta)} \tag{8}$$

Substituting (8) into (7), (7) is rewritten as

$$p_1 = \frac{3Q_0}{4(\alpha-\beta)} - \frac{-3w_1+w_2-2c_R-2c_L}{8}$$
$$p_2 = \frac{3Q_0}{4(\alpha-\beta)} - \frac{-3w_2+w_1-2c_R-2c_L}{8} \tag{9}$$

The manufacturer i uses the best reaction functions of the 3PL provider and the retailer to determine w_i to maximize its profit. Substituting (9) into (2) and (3), respectively, and applying the first-order conditions $\partial \prod_{M1} / \partial w_1 = 0$, $\partial \prod_{M2} / \partial w_2 = 0$ gives the optimal wholesale prices w_1^* and w_2^*. Hence, the optimal prices and profits of chain members are obtained by substituting w_1^* and w_2^* into corresponding equalities. The optimal results are reported in Table 1.

IV. SUB-COORDINATION IN THE SUPPLY CHAIN

In this section, three types of sub-coordination, i.e., the R-L coordination, the M-L coordination, and the M-R coordination, are discussed. The present model focuses to show the impact of sub-coordination on the supply chain using the fully decentralized supply chain as a benchmark. Comparing the optimal results under the sub-coordination with those under the fully decentralized supply chain, we aim to analyze whether the double marginalization is partly mitigated by the sub-coordination, and whether the sub-coordination is always effective to improve the profit of the supply chain.

A. R-L COORDINATION

The coordination only between the retailer and the 3PL provider can be achieved by two ways. The first one is that a flexible coordinating contract is established between the retailer and the 3PL provider [39]. The flexible coordinating contract means that they just set the rules of pricing while postponing the determination of the final contract prices, all they need to do is to declare that m and p_i will be determined based on the following rules: for given w_i,

$$m - c_L = \varphi(p_1 - w_1 - c_L - c_R) = \varphi(p_2 - w_2 - c_L - c_R)$$

where $0 < \varphi < 1$. Under these rules of pricing, $\prod_L = \varphi(\prod_R + \prod_L)$, $\prod_R = (1-\varphi)(\prod_R + \prod_L)$. φ implies the profit division between the retailer and the 3PL provider. Such a coordinating contract ensures that the retailer and the 3PL provider are always fully coordinated no matter what contract the manufacturers and the retailer agree on. The second one is that the retailer and the 3PL provider are owned by a firm, for example, the retailer can ship the products to the destination market with its own transportation fleet, warehouse and so on. When the retailer and the 3PL provider form the R-L coordination, the coordinated retailer-3PL provider decides p_1 and p_2 to maximize its total profits considering the logistics service price m as an interior payment. The coordinated retailer-3PL provider's profit function ${}_{RL}\prod_{R,L}$, manufacturer 1's profit function ${}_{RL}\prod_{M1}$, manufacturer 2's profit function ${}_{RL}\prod_{M2}$ can be expressed as

$$ {}_{RL}\prod_{R,L} = \Pi_R + \Pi_L = \sum_{i=1}^{2}(p_i - w_i - c_L - c_R)(Q_0 - \alpha p_i + \beta p_j) \tag{10}$$

$$ {}_{RL}\prod_{M1} = (w_1 - c_M)(Q_0 - \alpha p_1 + \beta p_2) \tag{11}$$

$$ {}_{RL}\prod_{M2} = (w_2 - c_M)(Q_0 - \alpha p_2 + \beta p_1) \tag{12}$$

The sequence of events taking place within this system is as follows. (1) The Manufacturer i determines the wholesale price w_i to the coordinated retailer-3PL provider. (2) The

TABLE 2. Optimal solutions under the R-L coordination.

	Optimal prices	Optimal profits
M_1:	$_{RL}w_1^* = \dfrac{Q_0-(\alpha-\beta)(c_R+c_L)+\alpha c_M}{2\alpha-\beta}$	$_{RL}\prod_{M1}^* = \dfrac{\alpha}{2(2\alpha-\beta)^2}[Q_0-(\alpha-\beta)c]^2$
M_2:	$_{RL}w_2^* = \dfrac{Q_0-(\alpha-\beta)(c_R+c_L)+\alpha c_M}{2\alpha-\beta}$	$_{RL}\prod_{M2}^* = \dfrac{\alpha}{2(2\alpha-\beta)^2}[Q_0-(\alpha-\beta)c]^2$
R & 3PL:	$_{RL}p_1^* = {}_{RL}p_2^* = \dfrac{(3\alpha-2\beta)Q_0}{2(\alpha-\beta)(2\alpha-\beta)} + \dfrac{\alpha c}{2(2\alpha-\beta)}$	$_{RL}\prod_{R,L}^* = \dfrac{\alpha^2}{2(\alpha-\beta)(2\alpha-\beta)^2}[Q_0-(\alpha-\beta)c]^2$
the supply chain:	N/A	$_{RL}\prod_{T}^* = \dfrac{\alpha(3\alpha-2\beta)}{2(\alpha-\beta)(2\alpha-\beta)^2}[Q_0-(\alpha-\beta)c]^2$

coordinated retailer-3PL provider ships the products to the destination market and determines retail prices p_1 and p_2 to the customers. Similar to Section 4, the optimal prices and profits of chain members are obtained. The optimal results are reported in Table 2.

Note that the degree of product substitutability is related to ρ, i.e., as ρ approaches 1, the two products become more substitutable. Most of the existing literature on the competing supply chain is concerned with the effects of the parameter ρ on supply chain performance. Thus, it is necessary to discuss that how sub-coordination affects the supply chain under different degrees of product substitutability.

Proposition 1: Comparing the optimal profits, the effects of the R-L coordination on the chain members under different degrees of product substitutability are given by the following:

(1) If ρ satisfies

$$4(5-\rho)^2 - 3(2-\rho)^2(3+\rho)^2 = z_1(\rho) \geq 0, \quad \text{i.e., } 0.56 \leq \rho < 1$$

then $_{RL}\prod_{R,L}^* \geq \prod_R^* + \prod_L^*$. How $z_1(\rho)$ changes with ρ is shown in Fig.2 (A). For comparative purposes, the profit improvement of the coordinated retailer-3PL provider is defined as $\Delta_1 = [_{RL}\prod_{R,L}^* - (\prod_R^* + \prod_L^*)]/(\prod_R^* + \prod_L^*)$. Δ_1 involves only the parameter ρ, the trend of Δ_1 over the range of product substitutability, as shown in Fig.2 (B).

(2) $_{RL}\prod_{M1}^* = {}_{RL}\prod_{M2}^* > \prod_{M1}^* = \prod_{M2}^*$, $_{RL}\prod_T^* > \prod_T^*$. For comparative purposes, the profit improvements of the manufacturers and the whole supply chain are defined as $\Delta_2 = (_{RL}\prod_{M1}^* - \prod_{M1}^*)/\prod_{M1}^*$ and $\Delta_3 = (_{RL}\prod_T^* - \prod_T^*)/\prod_T^*$, respectively. Δ_2 and Δ_3 involve only the parameter ρ, the trend of Δ_2 and Δ_3 over the range of product substitutability are shown in Fig.2 (C) and (d), respectively.

Proposition 1 shows that the performance of the R-L coordination critically depends on the degree of product substitutability. If the degree of product substitutability is high, i.e., $0.56 \leq \rho < 1$, the retailer and the 3PL provider would have incentives to form the R-L coordination and their total profits will increase. Moreover, Δ_1 is increasing in ρ (see Fig.2 (B)), that is, the more substitutable the two products become, the better the retailer and the 3PL provider form the R-L coordination. Fig.2 (B) also reveals that as ρ approaches 1, Δ_1 approaches 0.33, i.e. the profit of the coordinated retailer-3PL provider could increase by so far as to 33%. On the contrary, if the degree of product substitutability is low, i.e., $0 < \rho < 0.56$, the incentives for the retailer and the 3PL provider to form the R-L coordination disappear. Proposition 1 also shows that when the R-L coordination is formed, the profits of the two manufacturers and the whole supply chain will increase. Moreover, Δ_2 is increasing in ρ and $1.08 < \Delta_2 < 3.0$ (see Fig.2 (C)), i.e., the more substitutable the two products become, the greater the profit improvement of the manufacturers will be. The profit of the manufacturers could increase by 108% to 300% over the range of product substitutability. The two manufacturers greatly benefit from the R-L coordination and they will be very glad to see that the R-L coordination is formed. To the whole supply chain, the efficiency of the R-L coordination is greater than that of the decentralized supply chain. The double marginalization is partly mitigated by the coordination between the retailer and the 3PL provider. Moreover, Δ_3 is decreasing in ρ and $0.33 < \Delta_3 < 0.47$ (see Fig.2 (D)), i.e., the more substitutable the two products become, the worse the efficiency of the R-L coordination will be, and the profit of the whole supply chain could increase by 33% to 47% over the range of product substitutability.

B. M-L COORDINATION

The coordination only between the manufacturers and the 3PL provider can be achieved by two ways. The first one is that a flexible coordinating contract is established between the manufacturers and the 3PL provider. All they need to do is to declare that the logistics service price m and the wholesale price w_i will be determined based on the following expression

$$(1-\varphi)(m-c_L) = \varphi(w_1-c_M) = \varphi(w_2-c_M)$$

where $0 < \varphi < 1$. Under this contract, $\prod_L = \varphi(\prod_{M1} + \prod_{M2} + \prod_L)$, $\prod_{M1} = \prod_{M2} = [(1-\varphi)/2](\prod_{M1} + \prod_{M2} + \prod_L)$. φ implies the profit division

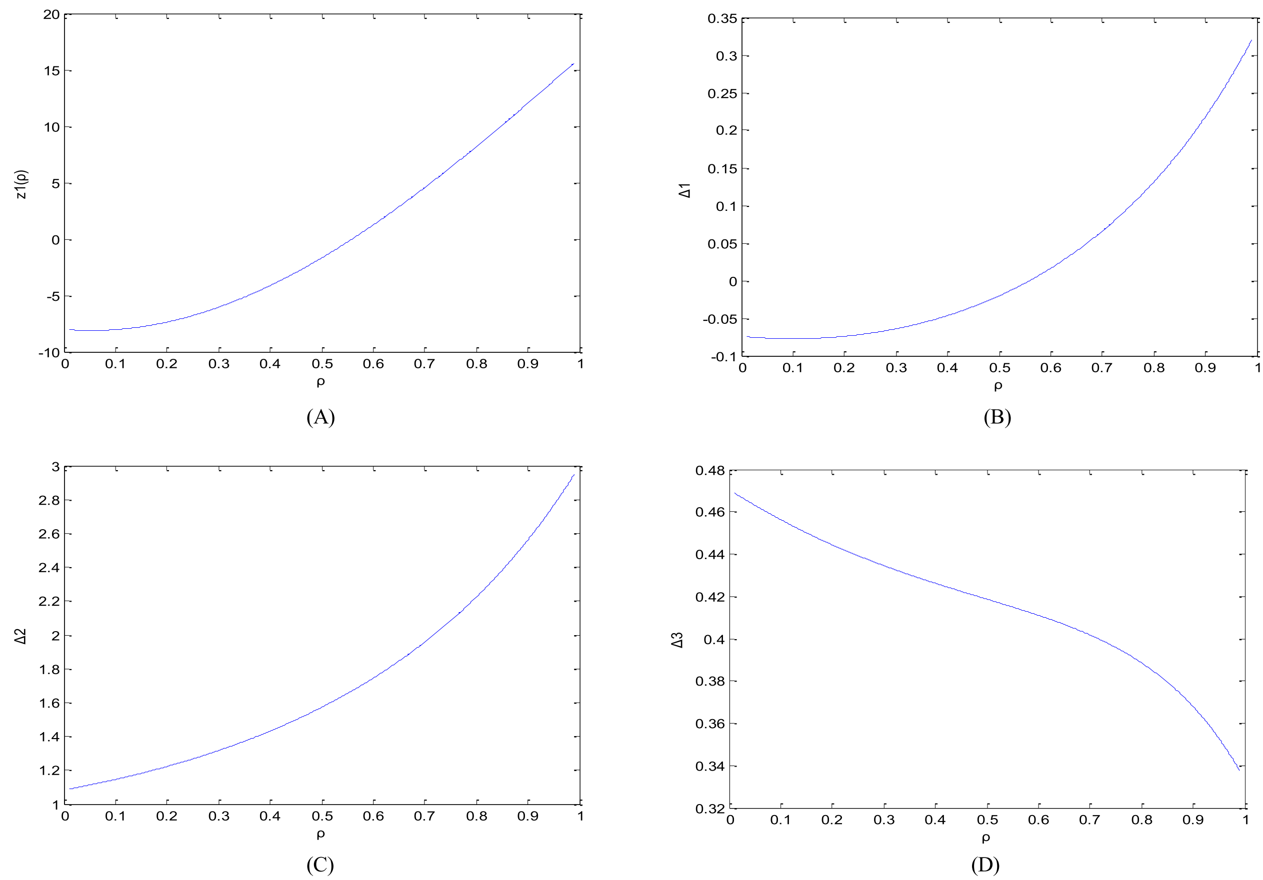

FIGURE 2. **The trend of $z_1(\rho)$, Δ_1, Δ_2 and Δ_3 over the range of product substitutability.**

between the manufacturers and the 3PL provider. Such a coordinating contract ensures that the manufacturers and the 3PL provider are always fully coordinated no matter what contract the 3PL provider and the retailer agree on. The second one is that the manufacturers ship the products to the destination market with their own transportation fleet, warehouse, and so on. When the manufacturers and the 3PL provider form the M-L coordination, the coordinated manufacturers-3PL provider decides $w_1 + m$ and $w_2 + m$ to maximize its total profits. The coordinated manufacturers-3PL provider's profit function ${}_{ML}\prod_{M1,M2,L}$, the retailer's profit function ${}_{ML}\prod_R$ can be expressed as

$$
\begin{aligned}
{}_{ML}\prod_{M1,M2,L} &= \prod_{M1} + \prod_{M2} + \prod_{L} \\
&= \sum_{i=1}^{2}(w_i + m - c_M - c_L)(Q_0 - \alpha p_i + \beta p_j)
\end{aligned} \tag{13}
$$

$$
{}_{ML}\prod_R = \sum_{i=1}^{2}(p_i - w_i - m - c_R)(Q_0 - \alpha p_i + \beta p_j) \tag{14}
$$

Similar to Section 4, the optimal prices and profits of the chain members are obtained. The optimal results are reported in Table 3.

Proposition 2: Comparing the optimal profits, the effects of the M-L coordination on the chain members under different degrees of product substitutability are given by the following:

(1) ${}_{ML}\prod^*_{M1,M2,L} < \prod^*_{M1} + \prod^*_{M2} + \prod^*_{L}$, ${}_{ML}\prod^*_R > \prod^*_R$. For comparative purposes, the profit loss of the coordinated manufacturers-3PL provider is defined as

$$
\Delta_4 = \frac{{}_{ML}\prod^*_{M1,M2,L} - (\prod^*_{M1} + \prod^*_{M2} + \prod^*_{L})}{\prod^*_{M1} + \prod^*_{M2} + \prod^*_{L}}
$$

The profit improvement of the retailer is defined as $\Delta_5 = ({}_{ML}\prod^*_R - \prod^*_R)/\prod^*_R$. Δ_4 and Δ_5 involve only the parameter ρ, the trend of Δ_4 and Δ_5 over the range of product substitutability are shown in Fig.3 (A) and (B), respectively.

(2) If ρ satisfies

$$
\begin{aligned}
&4(5-\rho)^2 - (2-\rho)(3+\rho)(17-5\rho) \\
&\quad = z_2(\rho) \geq 0, \quad \text{i.e., } 0.2 \leq \rho < 1
\end{aligned}
$$

then ${}_{ML}\prod^*_T \geq \prod^*_T$. How $z_2(\rho)$ changes with ρ is shown in Fig.3(C). For comparative purposes, the profit improvement of the entire supply chain is defined as $\Delta_6 = ({}_{ML}\prod^*_T - \prod^*_T)/\prod^*_T$. Δ_6 involves only the parameter ρ, the trend of Δ_6 over the range of product substitutability is shown in Fig.3 (D).

TABLE 3. Optimal solutions under the M-L coordination.

Optimal prices	Optimal profits
M_1 & M_2 & 3PL: ${}_{ML}(w_1+m)^* = {}_{ML}(w_2+m)^* = \dfrac{Q_0+\alpha(c_M+c_L)-(\alpha-\beta)c_R}{2\alpha-\beta}$	${}_{ML}\prod^*_{M1,M2,L} = \dfrac{\alpha}{2(2\alpha-\beta)^2}[Q_0-(\alpha-\beta)c]^2$
R: ${}_{ML}p_1^* = {}_{ML}p_2^* = \dfrac{(3\alpha-2\beta)Q_0}{2(\alpha-\beta)(2\alpha-\beta)} + \dfrac{\alpha\cdot c}{2(2\alpha-\beta)}$	${}_{ML}\prod^*_R = \dfrac{\alpha^2}{2(\alpha-\beta)(2\alpha-\beta)^2}[Q_0-(\alpha-\beta)c]^2$
the supply chain: N/A	${}_{ML}\prod^*_T = \dfrac{\alpha}{2(\alpha-\beta)(2\alpha-\beta)}[Q_0-(\alpha-\beta)c]^2$

Proposition 2 shows that if the manufacturers and the 3PL provider form the M-L coordination, their total profits will decrease and they would prefer to act alone rather than to coordinate with each other. Moreover, the loss rate $|\Delta_4|$ is increasing in ρ (see Fig.3 (A)), that is, the more substitutable the two products become, the worse the manufacturers and the 3PL provider form the M-L coordination, and they will be more interested in acting alone. Fig.3 (A) also reveals that $0.41 < |\Delta_4| < 1$, i.e., the profit of the coordinated manufacturers-3PL provider could decrease by 41% to 100% over the range of product substitutability. To the retailer, when the M-L coordination is formed, the profit of the retailer will increase. Moreover, Δ_5 is increasing in ρ and $1.78 < \Delta_5 < 3$ (see Fig.3 (B)), i.e., the more substitutable the two products become, the greater the profit improvement of the retailer will be. The profit of the retailer could increase by 178% to 300% over the range of product substitutability. To the entire supply chain, the efficiency of the M-L coordination depends on the degree of product substitutability. If the degree of product substitutability is very low, i.e., $0 < \rho < 0.2$, the M-L coordination enables the profit of the whole supply chain to decrease, and the profit could decrease by 2% at most. On the contrary, if $0.2 \le \rho < 1$, the M-L coordination enables the profit of the whole supply chain to increase, and the profit could increase by 33% at most.

C. M-R COORDINATION

The coordination only between the manufacturers and the retailer can be achieved by two ways. The first one is that a flexible coordinating contract is established between the manufacturers and the retailer. All they need to do is to declare that the wholesale price w_i and the retail price p_i will be determined based on the following expression: for given m, $w_i + c_R - \varphi(c_M + c_R) = (1-\varphi)(p_i - m)$, where $0 < \varphi < 1$. Under this contract, $\prod_R = \varphi(\prod_{M1} + \prod_{M2} + \prod_R)$, $\prod_{M1} = \prod_{M2} = [(1-\varphi)/2](\prod_{M1} + \prod_{M2} + \prod_R)$. φ implies the profit division between the manufacturers and the retailer. Such a coordinating contract ensures that the manufacturers and the retailer are always fully coordinated no matter what contract the 3PL provider and the retailer agree on. The second one is that the manufacturers distribute products through their wholly owned retail channel, such as the online channel. When the manufacturers and the retailer form the M-R coordination, the coordinated manufacturers-retailer decides p_1 and p_2 to maximize its total profits considering the wholesale prices w_1 and w_2 as interior payments. The coordinated manufacturers-retailer's profit function ${}_{MR}\prod_{M1,M2,R}$, the 3PL provider's profit function ${}_{MR}\prod_L$ can be expressed as

$$\begin{aligned} {}_{MR}\prod_{M1,M2,R} &= \prod_{M1} + \prod_{M2} + \prod_R, \\ &= \sum_{i=1}^{2}(p_i - m - c_M - c_R)(Q_0 - \alpha p_i + \beta p_j) \end{aligned} \tag{15}$$

$${}_{MR}\prod_L = \sum_{i=1}^{2}(m - c_L)(Q_0 - \alpha p_i + \beta p_j) \tag{16}$$

Similar to Section 4, the optimal prices and profits of the chain members are obtained. The optimal results are reported in Table 4.

Proposition 3: Comparing the optimal profits, as summarized in Tables 1 and 4, we find out that: ${}_{MR}\prod^*_L > \prod^*_L$, ${}_{MR}\prod^*_{M1,M2,R} < \prod^*_{M1} + \prod^*_{M2} + \prod^*_R$, ${}_{MR}\prod^*_T > \prod^*_T$. For comparative purposes, the profit loss of the coordinated manufacturers-retailer is defined as

$$\Delta_7 = \frac{{}_{MR}\prod^*_{M1,M2,R} - (\prod^*_{M1} + \prod^*_{M2} + \prod^*_R)}{\prod^*_{M1} + \prod^*_{M2} + \prod^*_R}$$

The profit improvements of the 3PL provider and the entire supply chain are defined as $\Delta_8 = ({}_{MR}\prod^*_L - \prod^*_L)/\prod^*_L$ and $\Delta_9 = ({}_{MR}\prod^*_T - \prod^*_T)/\prod^*_T$, respectively. Δ_7, Δ_8, and Δ_9 involve only the parameter ρ, the trend of Δ_7, Δ_8, and Δ_9 over the range of product substitutability are shown in Fig.4 (A)-(C), respectively.

Proposition 3 shows that if the manufacturers and the retailer form the M-R coordination, their total profits will decrease and they would prefer to act alone rather than to coordinate with each other. Moreover, if $0.2 < \rho < 1$, then $|\Delta_7|$ is decreasing in ρ, or else $|\Delta_7|$ is increasing in ρ. Proposition 3 also shows that the M-R coordination enables the profits of the 3PL provider and the entire supply chain to increase. Moreover, Δ_8 is decreasing in ρ and $0 < \Delta_8 < 1.78$ (see Fig.4 (B)), i.e., the more substitutable the two products become, the less the 3PL provider's profit improvement will

TABLE 4. Optimal solutions under the M-R coordination.

Optimal prices		Optimal profits
M₁ & M₂ & R:	$_{MR}p_1^* = {}_{MR}p_2^* = \frac{3Q_0 + (\alpha-\beta)c}{4(\alpha-\beta)}$	$_{MR}\Pi_{M1,M2,R}^* = \frac{1}{8(\alpha-\beta)}[Q_0-(\alpha-\beta)c]^2$
3PL:	$_{MR}m^* = \frac{Q_0-(\alpha-\beta)(c_R+c_M-c_L)}{2(\alpha-\beta)}$	$_{MR}\Pi_L^* = \frac{1}{4(\alpha-\beta)}[Q_0-(\alpha-\beta)c]^2$
the entire supply chain:	N/A	$_{MR}\Pi_T^* = \frac{3}{8(\alpha-\beta)}[Q_0-(\alpha-\beta)c]^2$

be, and the profit of the 3PL provider could increase by so far as to 178%. To the entire supply chain, Δ_9 is decreasing in ρ and $0 < \Delta_9 < 0.47$ (see Fig.4 (C)), i.e., the more substitutable the two products become, the worse the efficiency of the M-R coordination will be, and the profit of entire supply chain could increase by so far as to 47%.

D. ANALYSIS OF THREE TYPES OF SUB-COORDINATION

We proceed to analyze the equilibrium results derived in the previous section. In this study, we focus on the effects of three types of sub-coordination on the retailer's order quantities and the total profits of the entire supply chain. We show clearly which one is the best among three types of sub-coordination.

Proposition 4: The ordinal relationship of the retailer's order quantities at equilibrium under three types of sub-coordination is given below

$$q_1^* = q_2^* < {}_{MR}q_1^* = {}_{MR}q_2^* < {}_{RL}q_1^* = {}_{RL}q_2^* = {}_{ML}q_1^* = {}_{ML}q_2^*.$$

Proposition 4 indicates that three types of sub-coordination enable the retailer's order quantities to increase compared to the fully decentralized system, and ${}_{RL}q_1^* = {}_{RL}q_2^* = {}_{ML}q_1^* = {}_{ML}q_2^*$ implies that no matter what party the 3PL provider chooses to form sub-coordination with, the retailer's order quantities do not change. Among three types of sub-coordination, the retailer's order quantities under the R-L (or the M-L) coordination are the largest.

Proposition 5: Comparing the optimal profits of the entire supply chain, as summarized in the last ranks of Tables 1 to 4, we find out that

(1) If $0.67 < \rho < 1$, then ${}_{RL}\prod_T^* > {}_{ML}\prod_T^* > {}_{MR}\prod_T^* > \prod_T^*$.
(2) If $0.2 < \rho \leq 0.67$, then ${}_{RL}\prod_T^* > {}_{MR}\prod_T^* \geq {}_{ML}\prod_T^* > \prod_T^*$.
(3) If $0 < \rho \leq 0.2$, then ${}_{RL}\prod_T^* > {}_{MR}\prod_T^* > \prod_T^* \geq {}_{ML}\prod_T^*$.

Proposition 5 indicates that the effects of three types of sub-coordination on the total profits of the supply chain critically depend on the degree of product substitutability. For all $0 < \rho < 1$, the profit of the supply chain under the R-L coordination is the largest, i.e., the best choice for the entire supply chain is to let the retailer and the 3PL provider form sub-coordination. If $0.67 < \rho < 1$, no matter what party the manufacturers chooses to form sub-coordination with, the total supply chain profits will increase compared to the fully decentralized system, however, from the point of view of the whole supply chain's profit, it is better for the manufacturers to choose to form sub-coordination with the 3PL provider rather than to form sub-coordination with the retailer. If $0.2 < \rho \leq 0.67$, no matter what party the manufacturers chooses to form sub-coordination with, the total supply chain profits will increase compared to the fully decentralized system, however, from the point of view of the whole supply chain's profit, it is better for the manufacturers to choose to form sub-coordination with the retailer. If $0 < \rho \leq 0.2$, the M-L coordination is the worst, it's performance is even less than that in fully decentralized system.

V. NUMERICAL EXAMPLES

This section discusses the effects of sub-coordination on the supply chain through a numerical example. The demand function $q_i = 125 - 13p_i + 3.5p_j$. The manufacturer's cost $c_M = 10$, the 3PL provider's cost $c_L = 6.5$, the retailer's cost $c_R = 6$. Under the fully decentralized system, the optimal prices and profits of chain members are

$$w_1^* = w_2^* = 7.11, \quad p_1^* = p_2^* = 14.77, \; m^* = 3.27,$$
$$\Pi_{M1}^* = \Pi_{M2}^* = 44.25, \quad \Pi_R^* = 49.49, \; \Pi_L^* = 98.99.$$

Under the R-L coordination, the optimal prices and profits of chain members are

$$_{RL}w_1^* = {}_{RL}w_2^* = 6.06, \quad {}_{RL}p_1^* = {}_{RL}p_2^* = 15.86,$$
$$_{RL}\Pi_{M1}^* = {}_{RL}\Pi_{M2}^* = 101.13, \quad {}_{RL}\Pi_{R,L}^* = 138.39.$$

Under the M-L coordination, the optimal prices and profits of chain members are

$$_{ML}(w_1+m)^* = {}_{ML}(w_2+m)^* = 12.56,$$
$$_{ML}p_1^* = {}_{ML}p_2^* = 15.86,$$
$$_{ML}\Pi_{M1,M2,L}^* = 101.13, \quad {}_{ML}\Pi_R^* = 138.39.$$

Under the M-R coordination, the optimal prices and profits of chain members are

$$_{MR}p_1^* = {}_{MR}p_2^* = 15.49, \quad {}_{MR}m^* = 1.83,$$
$$_{MR}\Pi_{M1,M2,R}^* = 103.64, \quad {}_{MR}\Pi_L^* = 207.28.$$

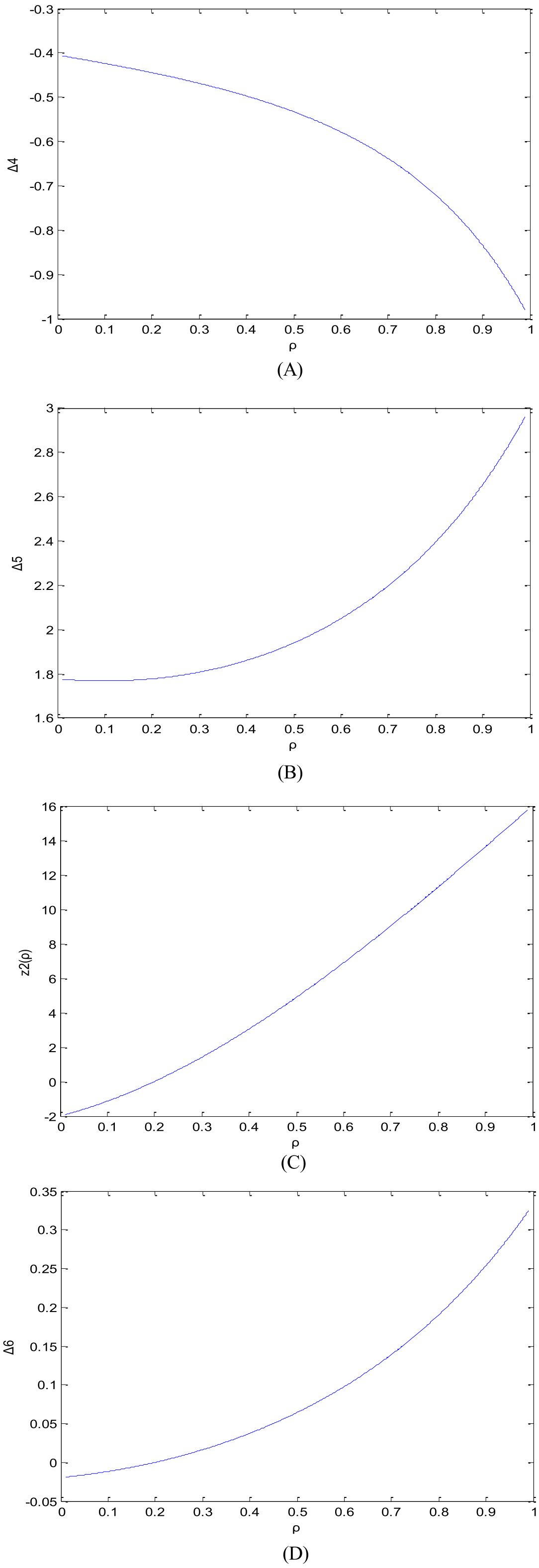

FIGURE 3. **The trend of Δ_4, Δ_5, $z_2(\rho)$ and Δ_6 over the range of product substitutability.**

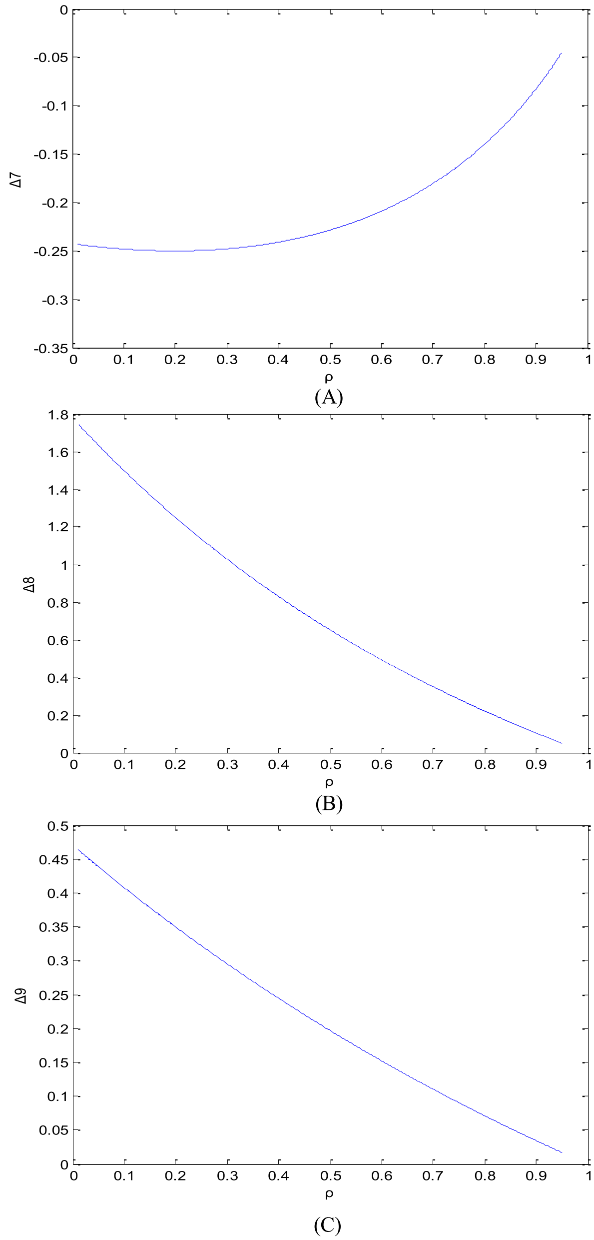

FIGURE 4. **The trend of Δ_7, Δ_8, and Δ_9 over the range of product substitutability.**

A. CASE 1

We examine the effects of sub-coordination on the profits of chain members. When the retailer and the 3PL provider form the R-L coordination, the profit of the coordinated retailer-3PL provider decreases by 6.8%, the profits of the manufacturers increase by 128.5%, the profit of the entire supply chain increases by 43.7%. When the manufacturers and the 3PL provider form the M-L coordination, the profit of the coordinated manufacturers-3PL provider decreases by 46.1%, the profit of the retailer increases by 179.6%, the profit of the entire supply chain increases by 1.1%. When the manufacturers and the retailer form the M-R coordination, the profit of the coordinated manufacturers-retailer decreases by 24.9%, the profit the 3PL provider increases by 109.4%, the profit of the entire supply chain increases by 31.2%.

TABLE 5. Optimal solutions under the R-L coordination when β changes from 5 to 12.

β	${}_{RL}w_1^* = {}_{RL}w_2^*$	${}_{RL}p_1^* = {}_{RL}p_2^*$	$2_{RL}\Pi_{M1}^* = 2_{RL}\Pi_{M2}^*$	${}_{RL}\Pi_{R,L}^*$
5	7.38	17.75	89.18	72.45
6	8.38	19.37	34.32	31.88
7	9.47	21.40	3.90	3.90
8	10.69	24.10	6.23	8.15
9	12.06	27.90	55.10	89.54
10	13.59	33.88	167.10	363.77
11	15.33	45.17	369.78	1201.78
12	17.32	77.41	696.84	4529.48

TABLE 6. Optimal solutions under the M-L coordination when β changes from 5 to 12.

β	${}_{ML}(w_1+m)^* = {}_{ML}(w_2+m)^*$	${}_{ML}p_1^* = {}_{ML}p_2^*$	${}_{ML}\Pi_{M1,M2,L}^*$	${}_{ML}\Pi_R^*$
5	13.88	17.75	44.59	72.45
6	14.88	19.37	17.16	31.88
7	15.97	21.40	1.80	3.90
8	17.19	24.10	3.13	8.15
9	18.56	27.90	27.55	89.54
10	20.10	33.88	83.95	363.77
11	21.83	45.17	184.89	1201.78
12	23.82	77.41	348.42	4529.48

TABLE 7. Optimal solutions under the M-R coordination when β changes from 5 to 12.

β	${}_{MR}m^*$	${}_{MR}p_1^* = {}_{MR}p_2^*$	${}_{MR}\Pi_{M1,M2,R}^*$	${}_{MR}\Pi_L^*$
5	3.06	17.34	47.27	94.53
6	4.18	19.02	18.86	37.72
7	5.67	21.25	2.08	4.17
8	7.75	24.38	3.91	7.81
9	10.88	29.06	38.28	76.56
10	16.08	36.88	137.76	275.52
11	26.50	52.50	400.00	800.00
12	57.75	99.38	1313.28	2626.56

B. CASE 2

We examine the effects of product substitutability on the chain members. The demand function $q_i = 125 - 13p_i + \beta p_j$, where β changes from 5 to 12 at intervals of 1. The optimal prices and profits under the R-L coordination, the M-L coordination, and the M-R coordination are reported in Tables 5 to 7, respectively. Table 5 to 7 show that for a fixed $\alpha = 13$, when $\beta \to \alpha$, all the equilibrium prices are increasing in β and all the equilibrium profits display a trend of U Curve, i.e., they are decreasing in β and then increasing in β.

C. CASE 3

The effects of product substitutability on the total profits of the supply chain under different types of sub-coordination are examined. The demand function $q_i = 125 - \alpha p_i + \beta p_j$, where $\rho = \beta/\alpha$ changes from 0 to 1. The profit improvements of the entire supply chain under the M-L coordination, the R-L coordination and the M-R coordination are shown in Fig.5.

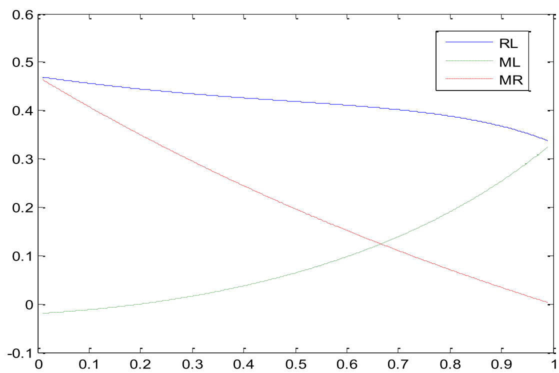

FIGURE 5. Profit improvements of the entire supply chain under different types of sub-coordination.

Fig.5 shows that the R-L coordination is the best among three types of sub-coordination, and if $0 < \rho \leq 0.67$, the M-R coordination is better than the M-L coordination, if $0.67 < \rho < 1$, the M-L coordination is better than the M-R coordination.

VI. CONCLUSION

We have investigated sub-coordination in a competing supply chain consisting of two manufacturers, a 3PL provider, and a retailer. Considering the difficulties of coordinating contracts for all members, three types of sub-coordination are explored. The conditions for some of them are willing to form sub-coordination and the effects of different types of sub-coordination on the supply chain are discussed. We find out that the effects critically depend on the degree of product substitutability. If the degree of product substitutability is high, the retailer and the 3PL provider would have incentives to form the R-L coordination and their total profits will increase. On the contrary, if the degree of product substitutability is low, the incentives for the retailer and the 3PL provider to form the R-L coordination disappear. Both the retailer and the 3PL provider would prefer to act alone rather than to coordinate with the manufacturers. From the point of view of the whole supply chain's profit, it is better to let the retailer and the 3PL provider form sub-coordination.

Our results provide some suggestions to managers and help them make better decisions. According to our results, sub-coordination is not always effective to improve the profit of the supply chain. To our surprise, in some cases sub-coordination even does harm to supply chain members or the whole supply chain. The performance of sub-coordination critically depends on the degree of product substitutability, managers should decide that whether or not form the sub-coordination and what kind of sub-coordination according to different degrees of product substitutability. If the degree of product substitutability is high, then R-L coordination is the best choice for the managers. If the degree of product substitutability is very low, it is better for the managers to choose not to coordinate with other chain members.

APPENDIX A
PROOF OF PROPOSITION 1

Proof: ${}_{RL}\prod_{M1}^{*} = {}_{RL}\prod_{M2}^{*} > \prod_{M1}^{*} = \prod_{M2}^{*}$ is equivalent to

$$\begin{aligned}&\alpha(5\alpha-\beta)^2-(3\alpha+\beta)(2\alpha-\beta)^2\\&\quad=13\alpha^3-2\alpha^2\beta+2\alpha\beta^2-\beta^3>0.\end{aligned}$$

Because $\beta < \alpha$, therefore

$$\begin{aligned}&13\alpha^3-2\alpha^2\beta+2\alpha\beta^2-\beta^3>13\alpha^3-2\alpha^3+2\alpha\beta^2-\alpha^3\\&\quad=10\alpha^3+2\alpha\beta^2>0.\end{aligned}$$

Therefore ${}_{RL}\prod_{M1}^{*} = {}_{RL}\prod_{M2}^{*} > \prod_{M1}^{*} = \prod_{M2}^{*}$.

APPENDIX B
PROOF OF PROPOSITION 2

Proof: ${}_{ML}\prod_{M1,M2,L}^{*} < \prod_{M1}^{*}+\prod_{M2}^{*}+\prod_{L}^{*}$ is equivalent to

$$2\alpha(\alpha-\beta)(5\alpha-\beta)^2-(2\alpha-\beta)^2(3\alpha+\beta)(7\alpha-3\beta)<0,$$

that is equivalent to

$$-34\alpha^4+22\alpha^3\beta+5\alpha^2\beta^2-12\alpha\beta^3+3\beta^4<0,$$

Because $\beta < \alpha$, therefore

$$\begin{aligned}&-34\alpha^4+22\alpha^3\beta+5\alpha^2\beta^2-12\alpha\beta^3+3\beta^4\\&\quad<-34\alpha^4+22\alpha^4+5\alpha^4-12\alpha\beta^3+3\alpha^4\\&\quad=-4\alpha^4-12\alpha\beta^3<0.\end{aligned}$$

Therefore ${}_{ML}\prod_{M1,M2,L}^{*} < \prod_{M1}^{*}+\prod_{M2}^{*}+\prod_{L}^{*}$.
${}_{ML}\prod_{R}^{*} > \prod_{R}^{*}$ is equivalent to

$$4\alpha^2(5\alpha-\beta)^2-(2\alpha-\beta)^2(3\alpha+\beta)^2>0,$$

that is equivalent to

$$64\alpha^4-28\alpha^3\beta+15\alpha^2\beta^2-2\alpha\beta^3-\beta^4>0,$$

Because $\beta < \alpha$, therefore

$$\begin{aligned}&64\alpha^4-28\alpha^3\beta+15\alpha^2\beta^2-2\alpha\beta^3-\beta^4\\&\quad>64\alpha^4-28\alpha^4+15\alpha^2\beta^2-2\alpha^4-\alpha^4\\&\quad=43\alpha^4+15\alpha^2\beta^2>0.\end{aligned}$$

Therefore ${}_{MML}\prod_{R}^{*} > \prod_{R}^{*}$.

APPENDIX C
PROOF OF PROPOSITION 3

Proof: ${}_{MR}\prod_{M1,M2,R}^{*} < \prod_{M1}^{*}+\prod_{M2}^{*}+\prod_{R}^{*}$ is equivalent to

$$(5\alpha-\beta)^2-(11\alpha-7\beta)(3\alpha+\beta)<0,$$

that is equivalent to $\beta^2-\alpha^2<0$, clearly,

$${}_{MMR}\prod\nolimits_{M1,M2,R}^{*}<\prod\nolimits_{M1}^{*}+\prod\nolimits_{M2}^{*}+\prod\nolimits_{R}^{*}.$$

${}_{MR}\prod_{L}^{*} > \prod_{L}^{*}$ is equivalent to

$$(5\alpha-\beta)^2-(3\alpha+\beta)^2=16\alpha(\alpha-\beta)>0,$$

clearly, ${}_{MMR}\prod_{L}^{*} > \prod_{L}^{*}$.
${}_{MR}\prod_{T}^{*} > \prod_{T}^{*}$ is equivalent to

$$3(5\alpha-\beta)^2-(3\alpha+\beta)(17\alpha-5\beta)>0,$$

that is equivalent to $8(\alpha-\beta)(3\alpha-\beta)>0$, clearly, ${}_{MMR}\prod_{T}^{*} > \prod_{T}^{*}$.

APPENDIX D
PROOF OF PROPOSITION 4

Proof: ${}_{MR}q_1^{*}-q_1^{*}=\frac{(\alpha-\beta)[Q_0-(\alpha-\beta)c]}{2(5\alpha-\beta)}>0$,

$${}_{RL}q_1^{*}-{}_{MR}q_1^{*}=\frac{[Q_0-(\alpha-\beta)c]\beta}{4(2\alpha-\beta)}>0,$$

clearly, $q_1^{*}=q_2^{*}<{}_{MR}q_1^{*}={}_{MR}q_2^{*}<{}_{RL}q_1^{*}={}_{RL}q_2^{*}={}_{ML}q_1^{*}={}_{ML}q_2^{*}$.

APPENDIX E
PROOF OF PROPOSITION 5

Proof: ${}_{RL}\prod_T^* - {}_{ML}\prod_T^* = \frac{[Q_0-(\alpha-\beta)c]^2\alpha}{2(2\alpha-\beta)^2} > 0,$

$$ {}_{RL}\prod\nolimits_T^* - {}_{MR}\prod\nolimits_T^* = \frac{(4\alpha-3\beta)[Q_0-(\alpha-\beta)c]^2\beta}{8(\alpha-\beta)(2\alpha-\beta)^2} > 0. $$

$$ {}_{MR}\prod\nolimits_T^* - {}_{ML}\prod\nolimits_T^* = \frac{(2\alpha-3\beta)[Q_0-(\alpha-\beta)c]^2}{8(\alpha-\beta)(2\alpha-\beta)}, $$

if $2\alpha - 3\beta \geq 0$, i.e.,$\rho \leq 0.67$, then ${}_{MR}\prod_T^* \geq {}_{ML}\prod_T^*$, or else, ${}_{MR}\prod_T^* < {}_{ML}\prod_T^*$. According to Proposition 2 (2), Proposition 5 holds.

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