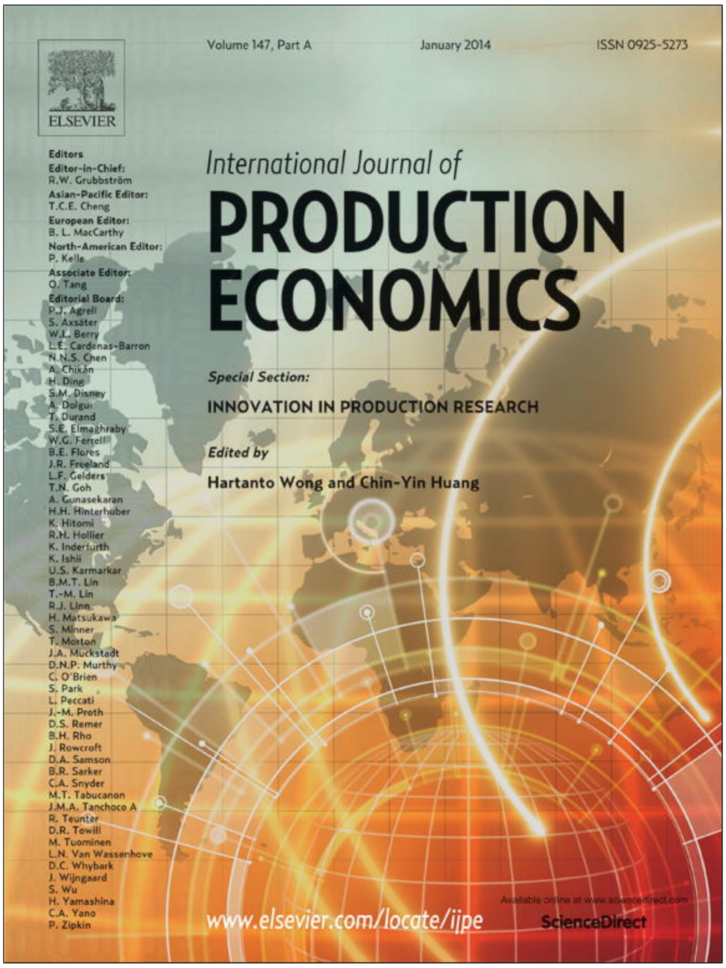
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# Revenue-sharing contracts in an N-stage supply chain with reliability considerations

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ABSTRACT

Revenue-sharing (RS) contracts have been used in a number of industries and have proven to be effective. However, the current RS contracts can be limited when improving the supply chain performance because of member reliability issues. This paper studies a revenue-sharing with reliability (RSR) contract in an N-stage supply chain. In this type of supply chain, there are more than two stages, and certain members have more than one upstream member. First, we propose an RSR contract that can coordinate supply chains and arbitrarily allocate total profits. A two-round profit allocation mechanism is utilized in this RSR contract. In the first round, an initial profit allocation scenario is decided; in the second round, the allocation is adjusted by considering the reliability of all of the members. A flexible method for adjusting the profits in the second round is proposed. Second, we study the incentives for the members to improve their reliability under the RS and RSR contracts by considering two realistic types of improvement investments in reliability. It is found that, in some cases, the RS contracts are limited in terms of encouraging the members to improve their reliability. Next, we show that there are greater incentives for members to improve their reliability under an RSR contract. We discuss in what cases the maximum possible profit of the supply chain under the RSR contract is higher than under the RS contract. Our analytical and numerical results yield insights into how managers can be encouraged to improve their reliability by setting certain decision variables.



## 1. Introduction

Supply chain coordination has attracted substantial attention from practitioners and academics. In a decentralized supply chain without a contract, the retailer orders fewer products than the global optimal quantity. This well-known phenomenon is called *double marginalization* (Spengler, 1950). Coordinating contracts are used to ensure channel coordination, though all members seek to maximize their own profits. Many popular types of contracts have been developed for supply chain coordination, including buy-back contracts (Pasternack, 1985), quantity-flexibility contracts (Tsay, 1999), and sales-rebate contracts (Taylor, 2002). A revenue-sharing (RS) contract is a popular contract that proved efficient for several industries. For example, revenue sharing increased the video industry's total profit by an estimated 7% (Cachon and Lariviere, 2005). We study a revenue-sharing with reliability (RSR) contract for a multi-stage supply chain that produces and sells a newsvendor-type product. Different suppliers supply different components to downstream members, and the final product is sold by a single retailer.

This study differs from previous work in three respects. First, we assume that each member has an imperfect production process. The assumption of "perfect production" is commonly used in current studies of supply chain contracts. Realistically, however, a supply chain member can rarely satisfy orders perfectly. For example, the average return rate of defects in the consumer electronics industry is approximately 3%, while the rate in the apparel industry is greater than 9% (Yoo et al., 2012). In this model, in addition to fulfilling the order quantity, suppliers send additional, free proportions of the order quantity to downstream members. The downstream members use these additional supplies to replace defective supplies, and the proportions decrease with suppliers' reliability levels. This model is common in the real world. For example, Higher Education Press (a large publishing company in China) sends orders to more than 30 printing plants. Without charging a fee, these plants send additional proportions of books to avoid stockouts from defective books. Proportions vary from 0.5% to 5%, depending on plants' reliability levels. To our knowledge, this supply chain model has rarely been considered in previous literature on supply chain contracts.

The second distinguishing aspect of this study is the RSR contract, which may generate a greater channel-wide profit compared with the

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**Nomenclature**

| | |
|---|---|
| $p$ | retail price of the final product |
| $s$ | salvage value of the final product, smaller than $p$ |
| $R(q)$ | total revenue of the retailer (Member 1) |
| $X$ | random variable representing the market demand, defined over continuous interval $[0,\infty)$ |
| $F(x)$ | cumulative probability function of $X$ |
| $f(x)$ | probability density function of $X$ |
| $n$ | number of members in the supply chain |
| $c_i$ | unit production cost of member $i$, $i=1,2,\ldots,n$ |
| $\overline{c}$ | vector of unit production costs of all of the members |
| $TR_i$ | reliability of member $i$, defined over the interval [0,1], $i=1,2,\ldots,n$ |
| $\overline{TR}$ | vector of reliabilities of all of the members |
| $TR_{av}$ | average reliability of the supply chain |
| $VR_i$ | $=TR_i–TR_{av}$, $i=1,2,\ldots,n$ |
| $\pi_i\ (\Phi_i,q)$ | expected profit of member $i$, $i=1,2,\ldots,n$ |
| $\pi_{sc}(q)$ | expected profit of the supply chain |
| $S_i$ | the set that contains member $i$, with all members being upstream from member $i$, $i=1,2,\ldots,n$ |
| $S_i'$ | the set that contains all members that are upstream from member $i$, $i=1,2,\ldots,n$ |
| $S_i''$ | the set that contains the members that are directly upstream from member $i$, $i=1,2,\ldots,n$ |
| $D_i$ | the set that contains member $i$, with all members being downstream from member $i$, $i=1,2,\ldots,n$ |
| $D_i'$ | the set that contains all members that are downstream from member $i$, $i=2,3,\ldots,n$ |
| $L_{\Delta\Phi i}$ | lower bound on $\Delta\Phi_i$ |
| $\pi_{T\_i}$ | profit threshold of member $i$, $i=1,2,\ldots,n$ |
| $\pi_{M\_i}$ | profit of member $i$ in the conventional market setting, $i=1,2,\ldots,n$ |
| $q^*$ | optimal quantity of the final product of the supply chain |
| $\Delta TR_i$ | increased reliability of member $i$, $i=1,2,\ldots,n$ |
| $\Delta c_i$ | increased unit production cost of member $i$, $i=1,2,\ldots,n$ |
| $\Delta\pi_{sc}$ | increased total profit when the reliability is improved |
| $\Delta\pi_i^k$ | increased profit of member $i$ when the reliability is improved under contract $k$, $i=1,2,\ldots,n$; $k=$RS,RSR |
| $TC_i^D$ | total development cost of member $i$ to improve his reliability, $i=1,2,\ldots,n$ |
| $\Phi_i^{RS}$ | member $i$'s total share of the revenue generated from each unit under the RS contract, $i=1,2,\ldots,n$ |
| $\omega_{M\_j}$ | price that member $j$ charges per unit in the conventional market setting, $j=2,3,\ldots,n$ |

*Decision variables*

| | |
|---|---|
| $q$ | order quantity of the final product that the supply chain produces |
| $\omega_j$ | wholesale price that member $j$ charges per unit, $j=2,3,\ldots,n$ |
| $\Phi_i$ | member $i$'s total share of the revenue generated from each unit, $i=1,2,\ldots,n$ |
| $\Phi_{F\_i}$ | member $i$'s basic share of the revenue generated from each unit, $i=1,2,\ldots,n$ |
| $\Delta\Phi_i$ | member $i$'s adjusted share of the revenue generated from each unit, $i=1,2,\ldots,n$ |

classic RS contract. Improved reliability can decrease extra supplies and thereafter, can decrease the cost per unit ordered. Consequently, the supply chain's total profit can be increased by improving its members' reliability. Under numerous previous contracts, however, some members might have insufficient incentive to improve their reliability. Under an RS contract, all members share the increased profits that accrue when the reliability of one member increases. If the member's increased profit is less than his investment in the improvement in reliability, then the member will not implement the improvement. In this case, the supply chain loses the opportunity to obtain a larger total profit (this phenomenon is demonstrated in detail in Section 3). To our knowledge, current research has not addressed how to design a coordinating contract that can encourage supply chain members to improve their reliability.

Third, we consider a multi-stage supply chain that has more than one member at some stages. Different members address different components, and the final product is sold by a single retailer. A laptop supply chain, for example, usually consists of a retailer, a manufacturer, and several suppliers. The suppliers produce different components for the manufacturer. The manufacturer finishes the assembly, and the retailer sells the laptops. Each type of component, such as the display, the hard drive, or the central processing unit, could be defective. The final product can also be defective because of imperfect retailer operation. Therefore, the supply chain's profit is influenced by the reliability of all its members. Hereafter, we refer to this type of supply chain as an N-stage supply chain. In such N-stage supply chains, the total profit increases as more members become coordinated. This finding is supported by the real-life practice of supply chain management, i.e., some contracts were used in N-stage supply chains and were efficient. For example, RS contracts have been used in the motion picture industry in Hollywood (Weinstein, 1998) and in the video rental industry (Mortimer, 2002). In Hollywood, RS contracts are used to coordinate some of the pop stars, producers, and distributors for some well-known movies, such as *Forrest Gump*. In the video rental industry, a third party firm joins the supply chain and helps to design the RS contracts that are agreed upon by the small rental firms. Based on such practical applications, members discuss their contracts, which can coordinate N-stage supply chains.

Some RS contracts for supply chain coordination have been developed. Cachon and Lariviere (2005) proposed an RS contract for use by a two-stage supply chain that consists of a retailer and a supplier. The decision variables are $(\omega, \Phi)$: the supplier charges the retailer a unit wholesale price of $\omega$ and a share $(1-\Phi)$ of the retailer's total revenue. Chauhan and Proth (2005) analyzed the supply chain partnership with revenue sharing. A method of maximizing total profit was proposed, and profit was allocated proportionally to member risk. Yao et al. (2008) discussed the performance of manufacturers under RS contacts and retailer competition. Giannoccaro and Ponatrandolfo (2009) proposed the negotiation of RS contracts in a two-stage supply chain. Li et al. (2009) developed a Nash bargaining model under a consignment contract with revenue sharing. Hou et al. (2009) extended the RS contract for a two-stage supply chain by incorporating inventory and lead times. Linh and Hong (2009) extended the RS contract in a two-period newsboy problem in which a two-buying-opportunities model was included. Pan et al. (2010) compared RS contracts with wholesale price contracts in different supply chain channels. Huang et al. (2011) designed a coordination mechanism to resolve a profit conflict in a reverse supply chain with false failure returns. These previous studies focused on two-stage supply chains. Coordinating contracts for three-stage supply chains have been discussed in several studies (e.g., Giannoccaro and Ponatrandolfo, 2004; Ding and Chen, 2008; van der Rhee et al., 2010). In all of these cases, a perfect product is assumed. In addition, these models addressed the problem of coordination in a supply chain with particular structures (e.g., serial structures).

Reliability is a popular index that is used to present a defective rate and to evaluate firm operations. Although the role of reliability in coordinating of supply chains has not been studied in the supply chain contract literature, it has been discussed in other fields of management. van Nieuwenhuyse and Vandaele (2006) studied the impact of delivery lot splitting on delivery reliability in a two-stage supply chain. Sana (2010) defined reliability as the proportion of defective products that can be influenced by the development cost. A similar definition is used in Sarkar (2012). Hsu and Li (2011) defined reliability as the probability that the initially proposed capacity of the plant would allow effective operation under demand fluctuations and developed a method of evaluating the performance of plants under demand fluctuations for supply chain networks. Aslam et al. (2011) developed a reliability sampling plan for minimizing the total cost while satisfying the reliability requirements; the median life of the Pareto distribution was used as a reliability measure. Yoon and Byun (2011) proposed a design for Six Sigma that can enhance the reliability in the aircraft industry. Yoo et al. (2012) studied one-time and continuous improvement investments in production and inspection reliability, which are defined as the proportion of defective items and the proportion of inspection failure during inspection. Tseng et al. (2012) studied green supply chain management by considering delivery reliability. Many studies have examined trust in the reliability of the operations that take place in the supply chain. Members with higher reliability can have higher trust values. Mun et al. (2009) introduced a goal-oriented fuzzy trust evaluation model in the context of a fractal-based virtual enterprise. The goal was to produce a product with high on-time performance, high quality, and normal cost. Oh et al. (2010) used a trust value to evaluate the reliability of supply chain members in collaborative fractal-based supply chains. Chen et al. (2010) suggested that reliability was an important part of trust and proposed a fuzzy method for evaluating trust, to improve knowledge sharing.

We attempt to develop an RSR contract that can coordinate the N-stage supply chain and can arbitrarily allocate the supply chain's profit. A two-round profit allocation mechanism is used in the RSR contract. Under the RSR contract, members can have a greater incentive to improve their reliability than under the RS contract. It is shown that, in some cases, the RSR contracts can bring a larger total profit of the supply chain than the RS contracts. Moreover, the RSR contract is independent of the approach used to evaluate the reliability. Therefore, our RSR contract is flexible, and the results of any reliability evaluation model can be used with such a contract.

This paper is organized as follows. The next section proposes an RSR contract for an N-stage supply chain. Section 3 describes a flexible method of adjusting profits with reference to an N-stage supply chain and Section 4 provides a numerical example. Finally, Section 5 offers managerial implications and concluding remarks.

## 2. RSR contract in an N-stage supply chain

Consider a supply chain comprising multiple stages, with more than being present one member at some stages. There are $n$ risk-neutral members, and one type of final product is sold by a single retailer. The retailer uses sole source procurement to purchase the final product. Different suppliers supply different components to the downstream members, and each supplier faces only one direct downstream member. Each member perfectly inspects the components delivered from the upstream member(s). Without compromising generality, we refer to Member 1 as the retailer. The retail price, the salvage value, the unit production cost, the number of members, and the reliability of the members are exogenous parameters. We assume that customers return defective products to the retailer and obtain replacements if the retailer's inventory is not empty; otherwise, customers obtain the retail price per defective product returned. Our model does not consider the goodwill penalty for lost sales and the long-run impact of poor product quality.

Under the RSR contracts, a member pays an upstream member a wholesale price for each unit ordered, and the upstream member sends additional components determined by the order quantity and by his reliability without charging a price. When the retailer determines the order quantity of the final product, $q$, the production quantity of member $i$ is $q/\prod_{k\in(D_i-D_1)} TR_k$, $i=2,3,\ldots,n$. The total production cost of the supply chain depends on $\bar{c}$, $\overline{TR}$, and $q$. When the selling season ends, the retailer can obtain a salvage value $s$ for each perfect unit that is unsold. All supply chain members share the retailer's total revenues. Fig. 1 illustrates a supply chain with six members. Member 1 is the retailer, Member 2 is the manufacturer, and Members 3 through 6 are the suppliers. Note that the unit production cost $c_i$ is a transformed cost. In some countries, for example, a cell phone contains two batteries, one of which is a spare battery. If the production cost per battery is \$20, then the production cost of the battery supplier is transferred to $\$40q/\prod_{k\in(D_i-D_1)} TR_k$.

Let

$$c = c_1 + \sum_{i=2}^{n} \frac{c_i}{\prod_{k\in(D_i-D_1)} TR_k} = TR_1 \sum_{i=1}^{n} \frac{c_i}{\prod_{k\in D_i} TR_k}$$

In the case of stochastic demand, the expected total profit function of the supply chain is

$$\pi_{sc}(q) = R(q) - cq = R(q) - c_1 q - \sum_{i=2}^{n} \frac{c_i}{\prod_{k\in(D_i-D_1)} TR_k} q \qquad (1)$$

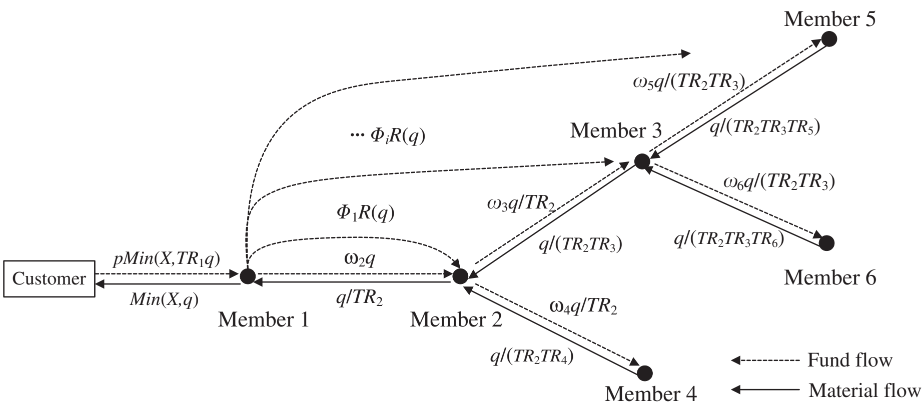


**Fig. 1.** An N-stage supply chain model.

The expected revenue of the retailer is

$$R(q) = p\left(\int_0^{TR_1 q} xf(x)dx + \int_{TR_1 q}^{\infty} TR_1 qf(x)dx\right) + s\int_0^{TR_1 q}(TR_1 q - x)f(x)dx \tag{2}$$

The expected marginal profit of the supply chain is

$$d\pi_{sc}(q)/dq = TR_1 p - TR_1(p-s)F(TR_1 q) - c \tag{3}$$

The expected marginal profit of the supply chain decreases with $q$; therefore, the expected marginal profit is 0 if and only if the order quantity is optimal. Let $q^*$ be the optimal order quantity of the supply chain. Based on Eq. (3), $q^*$ should satisfy

$$F(TR_1 q^*) = \frac{TR_1 p - c}{TR_1(p-s)} \tag{4}$$

**Lemma 1.** *The expected total profit of the supply chain is maximized when all members are coordinated.*

**Proof of Lemma 1.** Let a member be a terminal member if he has no upstream member. For simplicity, we only prove the lemma when one terminal member is not coordinated because the proofs of the other cases are similar. Assume that a terminal member, member $t$, is not coordinated. To obtain a positive profit, member $t$ charges a wholesale price per unit, $\omega_{M\_t}$ where

$$\omega_{M\_t} q TR_1 / \prod_{k \in D_t'} TR_k - c_t q TR_1 / \prod_{k \in D_t} TR_k > 0. \tag{5}$$

Because the other $n-1$ members are coordinated, the order quantity of the supply chain, $q^{(n-1)}$ satisfies

$$F(TR_1 q^{(n-1)}) = \frac{TR_1 p - c - \omega_{M\_t} TR_1 / \prod_{k \in D_t'} TR_k + c_t TR_1 / \prod_{k \in D_t'} TR_k}{TR_1(p-s)} \tag{6}$$

Therefore, $q^{(n-1)} < q^*$ and $\pi_{SC}(q^{(n-1)}) < \pi_{SC}(q^*)$. □

Lemma 1 shows that the supply chain's profit cannot be maximized unless all members are coordinated. Consequently, it is worthwhile to design a contract that covers all members simultaneously. Our RSR contract coordinates N-stage supply chains by making each member's profit function an affine transformation of the supply chain's profit function. Under the RSR contract, member $i$ shares $\Phi_i$ of the retailer's revenue, and $\sum_{i=1}^{n} \Phi_i = 1$. We can obtain member $i$'s profit function as follows, $i = 1,2,\ldots,n$.

If member $i$ is a terminal member, then

$$\pi_i(\Phi_i, q) = \Phi_i R(q) + \frac{\omega_i TR_1}{\prod_{k \in D_i'} TR_k} q - \frac{c_i TR_1}{\prod_{k \in D_i} TR_k} q \tag{7}$$

If member $i$ is neither a terminal member nor the retailer, then

$$\pi_i(\Phi_i, q) = \Phi_i R(q) + \omega_i \frac{TR_1 q}{\prod_{k \in D_i'} TR_k} - \left(\left(c_i + \sum_{j \in S_i''} \omega_j\right)\right) \frac{TR_1 q}{\prod_{k \in D_i} TR_k} \tag{8}$$

The retailer's expected profit is

$$\pi_1(\Phi_1, q) = \Phi_1 R(q) - c_1 q - \textstyle\sum_{j \in S_1''} \omega_j q. \tag{9}$$

**Theorem 1.** *Consider the set of RSR contracts with the following*:

$$\omega_j = \sum_{k \in S_j} \frac{c_k}{\prod_{u \in (D_k - D_j')} TR_u} - \sum_{k \in S_j} (\Phi_{F\_k} - \Delta\Phi_k) \frac{c}{TR_1} \prod\nolimits_{m \in D_j'} TR_m \tag{10}$$

Note that $\sum_{i=1}^{n} \Phi_{F\_i} = 1$, $\sum_{i=1}^{n} \Delta\Phi_i = 0$, and $\Phi_{F\_i} \in (0,1)$, $i = 1,2,\ldots,n$, $j = 2,3,\ldots,n$. Let the percentage that member $i$ retains be represented by the following:

$$\Phi_i = \Phi_{F\_i} + \Delta\Phi_i - 2cq\Delta\Phi_i / R(q) \tag{11}$$

Under those contracts, the profit function of member $i$ is

$$\pi_i(\Phi_i, q) = \pi_i(\Phi_{F\_i}, \Delta\Phi_i, q) = (\Phi_{F\_i} + \Delta\Phi_i)\pi_{sc}(q) \tag{12}$$

Therefore, member $i$ can obtain $\Phi_{F\_i} + \Delta\Phi_i$ of the supply chain's profit. Then, all of the members will choose the quantity that maximizes the total profit of the supply chain.

**Proof of Theorem 1.** Case 1 Member $i$ is a terminal member. Therefore, $S_i = \{i\}$. According to Eq. (10),

$$\begin{aligned}\omega_i \frac{TR_1 q}{\prod_{k \in D_i'} TR_k} &= \frac{c_i}{\prod_{u \in (D_i - D_i')} TR_u} \frac{TR_1 q}{\prod_{k \in D_i'} TR_k} - (\Phi_{F\_i} - \Delta\Phi_i) \frac{c}{TR_1} \prod_{m \in D_i'} TR_m \frac{TR_1 q}{\prod_{k \in D_i'} TR_k} \\ &= \frac{c_i TR_1 q}{\prod_{u \in D_i} TR_u} - (\Phi_{F\_i} - \Delta\Phi_i) cq\end{aligned} \tag{13}$$

By substituting Eqs. (11) and (13) into Eq. (7)

$$\begin{aligned}\pi_i(\Phi_i, q) &= (\Phi_{F\_i} + \Delta\Phi_i)R(q) + \omega_i \frac{TR_1 q}{\prod_{k \in D_i'} TR_k} - c_i \frac{TR_1 q}{\prod_{k \in D_i} TR_k} \\ &\quad - 2\Delta\Phi_i cq = (\Phi_{F\_i} + \Delta\Phi_i)R(q) - (\Phi_{F\_i} + \Delta\Phi_i)cq \\ &= (\Phi_{F\_i} + \Delta\Phi_i)\pi_{sc}(q)\end{aligned} \tag{14}$$

Case 2 Member $i$ is neither a terminal member nor the retailer. Because $\prod_{k \in D_i} TR_k = \prod_{m \in D_j'} TR_m$ for all $j \in S_i''$, the total cost of member $i$ is

$$\begin{aligned}&\sum_{j \in S_i''} \left(\omega_j \frac{TR_1 q}{\prod_{m \in D_j'} TR_m}\right) + c_i \frac{TR_1 q}{\prod_{k \in D_i} TR_k} \\ &= \sum_{j \in S_i''} \left(\sum_{k \in S_j} \frac{c_k}{\prod_{u \in (D_k - D_j')} TR_u} \frac{TR_1 q}{\prod_{m \in D_j'} TR_m} - \sum_{k \in S_j} (\Phi_{F\_k} - \Delta\Phi_k) cq\right) + c_i \frac{TR_1 q}{\prod_{k \in D_i} TR_k} \\ &= \sum_{j \in S_i''} \sum_{k \in S_j} \frac{c_k TR_1 q}{\prod_{u \in D_k} TR_u} - \sum_{k \in S_i'} (\Phi_{F\_k} - \Delta\Phi_k) cq + c_i \frac{TR_1 q}{\prod_{k \in D_i} TR_k} \\ &= \sum_{k \in S_i} \frac{c_k TR_1 q}{\prod_{u \in D_k} TR_u} - \sum_{k \in S_i'} (\Phi_{F\_k} - \Delta\Phi_k) cq\end{aligned} \tag{15}$$

By substituting Eqs. (10), (11), and (15) into Eq. (8), we obtain

$$\begin{aligned}\pi_i(\Phi_i, q) &= (\Phi_{F\_i} + \Delta\Phi_i)R(q) + \omega_i \frac{TR_1 q}{\prod_{k \in D_i'} TR_k} \\ &\quad - c_i \frac{TR_1 q}{\prod_{k \in D_i} TR_k} - \sum_{j \in S_i''} \left(\omega_j \frac{TR_1 q}{\prod_{m \in D_j'} TR_m}\right) - 2\Delta\Phi_i cq \\ &= (\Phi_{F\_i} + \Delta\Phi_i)R(q) + \sum_{k \in S_i} \frac{c_k TR_1 q}{\prod_{u \in D_k} TR_u} - \sum_{k \in S_i} \frac{c_k TR_1 q}{\prod_{u \in D_k} TR_u} \\ &\quad - (\Phi_{F\_i} - \Delta\Phi_i)cq - 2\Delta\Phi_i cq = (\Phi_{F\_i} + \Delta\Phi_i)\pi_{sc}(q)\end{aligned} \tag{16}$$

Case 3 Member $i$ is the retailer. Therefore, $i = 1$.

Noting that $\sum_{i=1}^{n} \Phi_{F\_i} = 1$ and $\sum_{i=1}^{n} \Delta\Phi_i = 0$, based on Eqs. (9)–(11),

$$\begin{aligned}\pi_1(q) &= (\Phi_{F\_i} + \Delta\Phi_i)R(q) - c_1 q - \sum_{j \in S_1''} \omega_j q - 2\Delta\Phi_1 cq \\ &= (\Phi_{F\_1} + \Delta\Phi_1)R(q) - \left(1 - \sum_{j=2}^{n} (\Phi_{F\_j} - \Delta\Phi_j)\right) cq - 2\Delta\Phi_1 cq \\ &= (\Phi_{F\_1} + \Delta\Phi_1)\pi_{sc}(q)\end{aligned} \tag{17}$$

Therefore, the profits of member $i$ are $(\Phi_{F\_i} + \Delta\Phi_i)\pi_{sc}(q)$, $i = 1,2,\ldots,n$. □

Under a fixed $\Phi_{F\_i} + \Delta\Phi_i$, each member can obtain a maximum profit when the supply chain's profit is maximized. Therefore, all of the members will accept the optimal order quantity for the supply chain and supply chain coordination is achieved. RSR contracts can also arbitrarily allocate profits in this type of supply chain by setting $\Phi_{F\_i}+\Delta\Phi_i$, $i=1,2,\ldots,n$. A two-round profit allocation mechanism is utilized in the RSR contract. In the first round, an initial profit allocation scenario is decided by setting $\Phi_{F\_i}$; in the second round, the allocation is adjusted by setting $\Delta\Phi_i$ based on the reliability of member $i$. The profit of member $i$ is a function of $\Phi_{F\_i}$, $\Delta\Phi_i$, and $q$, $i=1,2,\ldots,n$. The timing of the supply chain events under the RSR contract is as follows:

- Before the selling season, all of the members decide the profit allocation in the first round by setting $\Phi_{F\_i}$, $i=1,2,\ldots,n$.
- Based on the member reliability, the profit allocation is adjusted in the second round by setting $\triangle\Phi_i$, $i=1,2,\ldots,n$.
- All of the members decide the wholesale prices that they charge their direct downstream members. The retailer responds by placing an order for $q$ units of the final product.
- Production in the suppliers takes place, and the finished final products are delivered to the retailer.
- At the end of the selling season, the total revenue of the retailer is computed. Member $i$ obtains a share amounting to $\Phi_{F\_i}+\triangle\Phi_i-2cq\triangle\Phi_i/R(q)$ from the retailer's total revenue, $i=1,2,\ldots,n$.

A limitation of implementing supply chain contracts is the administrative cost. The administrative cost of the RS contract occurs because the supplier must monitor the retailer's revenues. Note that the information collected for the RS contract yields the information required to implement the RSR contracts. In addition, the timing of the supply chain events previously described is similar to the timing specified by the RS contract. If a supply chain switches from the RS contract to the RSR contract, managers must only modify the wholesale prices and revenue-sharing proportions using our model (Theorem 1). Consequently, the RS contract's administrative costs can also support the RSR contract. Real-life practice demonstrates the economics of RS contracts in N-stage supply chains. Therefore, an RSR contract for N-stage supply chains is also efficient in the real world.

**Remark 1.** The administrative cost of the RS contract can also support the RSR contract.

By determining $\Phi_i(=\Phi_{F\_i}+\Delta\Phi_i)$ and $\omega_i$ using Theorem 1, the RSR contract can achieve supply chain coordination, a basic requirement for coordinating contracts. To be more competitive than the RS contract, the RSR contract should achieve the following two objectives. First, it should generate a larger total profit than the RS contract does. To achieve this objective, members must have a greater incentive for improving their reliability under the RSR contract than under the RS contract because the maximum total profit of the supply chain can increase as members improve their reliability. Second, the RSR contract should generate a profit greater than the members' profit thresholds to sign the RSR contract. Therefore, it is important to set $\Phi_{F\_i}$ and $\triangle\Phi_i$ to achieve these two objectives. In the next section, the two-round profit allocation mechanism for designing such a *competitive* RSR contract is discussed.

## 3. Two-round profit allocation mechanism based on reliability

### 3.1. APA method

Under the two-round profit allocation mechanism, by setting $\triangle\Phi_i$, the members with a lower reliability could lose profit, which is transferred to other members. We propose an *Adjustment of Profit Allocation* (***APA***) method to decide $\triangle\Phi_i$ based on member reliability, thus adjusting the second round profit allocation such that competitive RSR contracts can be drafted. First, we discuss the lower bound of $\triangle\Phi_i$, $i=1,2,\ldots,n$. The RSR contract can be accepted by member $i$ when member $i$ obtain profits greater than his profit threshold, $\pi_{T\_i}$. Without compromising generality, we assume that a meaningful $\pi_{T\_i}$ should satisfy $\sum_{i=1}^{n}\pi_{T\_i}<\pi_{sc}(q^*)$ and $\pi_{T\_i}>0$, where $\pi_{sc}(q^*)$ is the maximum total profit of the supply chain. Thus, $(\Phi_{F\_i}+\triangle\Phi_i)\pi_{sc}(q^*)>\pi_{T\_i}>0$, and $\triangle\Phi_i$ has a lower bound ($L_{\triangle\Phi i}$):

$$L_{\Delta\Phi_i}=\pi_{T\_i}/\pi_{sc}(q^*)-\Phi_{F\_i},\quad i=1,2,\ldots,n \tag{18}$$

Given a fixed $\Phi_{F\_i}$, all $\triangle\Phi_i$ greater than $L_{\triangle\Phi i}$ make the RSR contract generate profits greater than $\pi_{T\_i}$ for member $i$, for all $i=1,2,\ldots,n$.

**Lemma 2.** *Under an RSR contract, $\Phi_{F\_i}$ should satisfy $\Phi_{F\_i}\Pi_{sc}(q^*)>\pi_{T\_i}$, and $L_{\triangle\Phi i}$ is less than 0, $i=1,2,\ldots,n$.*

**Proof of Lemma 2.** Because $\sum_{i=1}^{n}\Delta\Phi_i=0$, the profits of some members might decrease in the second round profit allocation, i.e., $\triangle\Phi_i<0$. To ensure that member $i$ can obtain a profit greater than $\pi_{T\_i}$, $\Phi_{F\_i}$ should satisfy $\Phi_{F\_i}\pi_{sc}(q^*)>\pi_{T\_i}$. According to Eq. (18), $L_{\triangle\Phi i}=\pi_{T\_i}/\pi_{sc}(q^*)-\Phi_{F\_i}<0$, $i=1,2,\ldots,n$. □

Given the reliability of all of the members, the *APA* method can be implemented by the following steps.

*Step 1*: Set the profit allocation in the first round with $\Phi_{F\_i}\pi_{sc}(q)>\pi_{T\_i}$.
*Step 2*: Calculate the average reliability of the supply chain as $TR_{av}=\sum_{i=1}^{n}TR_i/n$. Next, let $VR_i=TR_i-TR_{av}$.
*Step 3*: Let $\alpha_i=L_{\triangle\Phi i}/VR_i$ if $VR_i$ is negative; otherwise, let $\alpha_i$ be a large positive number.
*Step 4*: Let $\alpha$ be one value between $[0,\min\{\alpha_1,\ldots,\alpha_n\})$, and let $\triangle\Phi_i=\alpha VR_i$, $i=1,2,\ldots,n$.

By setting $\triangle\Phi_i=\alpha VR_i$ where $\alpha\geq0$, the members whose reliability levels are lower than the average reliability level ($TR_{av}$) could lose profits, which then are assigned to other members. Those members lose more profit when $\alpha$ is increased and profit allocation is adjusted. To satisfy the members' profit thresholds, an upper bound is established for $\alpha$ and is influenced only by $\alpha_i$ with $VR_i<0$. Because $L_{\triangle\Phi i}$ is less than 0, we obtain $\alpha_i>0$ for $i=1,2,\ldots,n$. Consequently, $\min\{\alpha_1,\ldots,\alpha_n\}$ is greater than 0, and $\alpha$ can be set to any value within the range $[0,\min\{\alpha_1,\ldots,\alpha_n\})$. Theorem 2 shows that by setting the value of $\alpha$ within this range, managers can adjust profit allocation and satisfy the profit thresholds of all members simultaneously.

**Theorem 2.** *Given any set $\pi_{T\_i}$ with $\pi_{T\_i}>0$ and $\sum_{i=1}^{n}\pi_{T\_i}<\pi_{sc}(q^*)$, under an RSR contract, all members obtain profits greater than their profit thresholds.*

**Proof of Theorem 2.** Suppose that member *i's* reliability level is greater than or equal to the average reliability level of the supply chain, i.e., $VR_i\geq0$. Because $\alpha\geq0$, we can infer that $\triangle\Phi_i=\alpha VR_i\geq0$. From Lemma 2, we know that $(\Phi_{F\_i}+\triangle\Phi_i)\pi_{sc}(q^*)\geq\Phi_{F\_i}\pi_{sc}(q^*)>\pi_{T\_i}$. Therefore, under the RSR contract, member $i$ obtains a profit greater than $\pi_{T\_i}$. When $VR_i<0$, we have $\triangle\Phi_i=\alpha VR_i<0$. Because $\alpha$ is a value within the range $[0,\min\{\alpha_1,\ldots,\alpha_n\})$, $\alpha VR_i>\alpha_i VR_i$. Step 3 of the *APA* method specifies that $\alpha_i VR_i=L_{\triangle\Phi i}$. Consequently, $\alpha VR_i>L_{\triangle\Phi i}$. Considering $(\Phi_{F\_i}+L_{\triangle\Phi i})\pi_{sc}(q^*)=\pi_{T\_i}$ and $\triangle\Phi_i=\alpha VR_i$, then

$$(\Phi_{F\_i}+\Delta\Phi_i)\pi_{sc}(q^*)>\pi_{T\_i} \tag{19}$$

Therefore, all members can obtain profits that exceed their profit thresholds. □

Because the RSR contract can support any set of $\pi_{T\_i}$ with $\pi_{T\_i} > 0$ and $\sum_{i=1}^{n} \pi_{T\_i} < \pi_{sc}(q^*)$, the supply chain's profit can be arbitrarily allocated. Under the *APA* method, the profit allocation in the first round must be decided. In a previous study, van der Rhee et al. (2010) discussed two easy and feasible scenarios (Scenarios *A* and *B*) for determining the profit allocation under RS contracts. In Scenario *A*, $\Phi_{F\_i} = \pi_{T\_i} / \sum_{i=1}^{n} \pi_{T\_i}$; while in Scenario *B*,

$$\Phi_{F\_i} = \left( \frac{\pi_{sc}(q^*) - \sum_{i=1}^{n} \pi_{T\_i}}{n\pi_{sc}(q^*)} + \frac{\pi_{T\_i}}{\pi_{sc}(q^*)} \right).$$

these options are easier for the supply chain to accept without a bargaining mechanism. We take these two scenarios as examples to discuss the impact of profit allocation in the first round ($\Phi_{F\_i}$).

**Theorem 3.** *When $\pi_{T\_i} / \sum_{i=1}^{n} \pi_{T\_i} > 1/n$, setting $\Phi_{F\_i}$ with Scenario A can support a larger range of $\triangle \Phi_i$ than with Scenario B, $i = 1,2,\ldots,n$.*

**Proof of Theorem 3.** Let $L^A_{\Delta\Phi_i}$ and $L^B_{\Delta\Phi_i}$ be $L_{\triangle \Phi i}$ in Scenarios *A* and *B*, respectively, $i = 1,2,\ldots,n$. Eq. (18) can be rewritten as

$$L^A_{\Delta\Phi_i} = \pi_{T\_i} / \pi_{sc}(q^*) - \pi_{T\_i} / \sum_{i=1}^{n} \pi_{T\_i} \tag{20}$$

$$L^B_{\Delta\Phi_i} = \frac{\pi_{T\_i}}{\pi_{sc}(q^*)} - \frac{\pi_{sc}(q^*) - \sum_{i=1}^{n} \pi_{T\_i} + n\pi_{T\_i}}{n\pi_{sc}(q^*)} \tag{21}$$

Then,

$$L^A_{\Delta\Phi_i} - L^B_{\Delta\Phi_i} = \frac{\left(\sum_{i=1}^{n} \pi_{T\_i} - n\pi_{T\_i}\right)\left(\pi_{sc}(q^*) - \sum_{i=1}^{n} \pi_{T\_i}\right)}{\pi_{sc}(q^*) \sum_{i=1}^{n} \pi_{T\_i}} \tag{22}$$

Because $\pi_{T\_i} / \sum_{i=1}^{n} \pi_{T\_i} > 1/n$ and $\sum_{i=1}^{n} \pi_{T\_i} < \pi_{sc}(q^*)$, we obtain $L^A_{\Delta\Phi_i} - L^B_{\Delta\Phi_i} < 0$ $i = 1,2,\ldots,n$. □

Theorem 3 shows that, under certain conditions, Scenario *A* is more flexible than Scenario *B* in terms of the profit allocation in the second round for certain members. Given a set of $\Phi_{F\_i}$, profits can be arbitrarily adjusted in the second round by setting the value of $\alpha$. If a member wants to obtain higher profits after the second round, that member should exhibit better than average reliability. It is obvious that there could be many different methods for allocating profits based on reliability. However, the *APA* method is competitive for the following three reasons. The *APA* method

(i) can arbitrarily adjust profits based on reliability;
(ii) can be used separately in different groups of members;
(iii) is independent of the reliability evaluation approach.

Reasons (ii) and (iii) are more important in terms of reliability. As we know, it is not easy to evaluate each member's reliability. Moreover, different members can play different roles and have different characteristics in the supply chain. Therefore, it is difficult to obtain a model for evaluating the reliability of these different members. Using the *APA* method, however, we can group members based on their characteristics in terms of reliability, and we can separately analyze each group. Then, the profits are arbitrarily adjusted for each group independently, and supply chain coordination can still be achieved. Conversely, there are many reliability evaluation approaches that are based on different definitions of reliability. Therefore, different supply chains can use different reliability evaluation models. The *APA* method is independent of the approach to reliability evaluation. It means that, given any set of reliability values, the *APA* method can be used to adjust the profits, which increases the usefulness of the RSR contract in real-world settings. In the next subsection, we compare the supply chain's profits under RSR and RS contracts.

### 3.2. Comparison of the RS and the RSR contracts

It is easy to prove that the expected total profit of the supply chain increases as member reliability improves. Members can improve their reliability by improving their investment (e.g., see Yoo et al., 2012; Sarkar, 2012; Sana, 2010). Two types of improvement investments for increasing reliability are typical. The first type of investment can be added into the unit production cost easily, and the new unit production cost can be agreed upon by all of the other members. For example, one member could use a more expensive and more reliable type of raw material in the production process. If the price of the new material is publicized, then the investment can be incorporated into the unit production cost easily.

According to Eq. (4), $q^*$ is a function of $\overline{TR}$ and $\overline{c}$. Denote $\pi_{sc}(q^* | \overline{TR}, \overline{c})$ as the maximum $\pi_{sc}(q)$ given $\overline{TR}$ and $\overline{c}$. Suppose that member $i$ increases his unit production cost by $\triangle c_i$ to improve his reliability and that the reliability improves by $\Delta TR_i$, $\triangle TR_i > 0$. The expected increased profit of the supply chain, $\triangle \pi_{sc}$, is $\Delta\pi_{sc} = \pi_{sc}(q^* | \overline{TR} + \Delta\overline{TR}, \overline{c} + \Delta\overline{c}) - \pi_{sc}(q^* | \overline{TR}, \overline{c})$, where $\Delta\overline{TR} = \{0, \ldots, \triangle TR_i, \ldots, 0\}$ and $\Delta\overline{c} = \{0, \ldots, \triangle c_i, \ldots, 0\}$. By setting $\triangle \Phi_i = 0$ in Theorem 1, we can obtain the profit of member $i$ under the RS contract. Let $\Phi_i^{RS}$ be member $i$'s share of the retailer's total revenue under the RS contract. Under the RS contract, the expected increased profit of member $i$ is

$$\Delta\pi_i^{RS} = \Phi_i^{RS} [\pi_{sc}(q^* | \overline{TR} + \Delta\overline{TR}, \overline{c} + \Delta\overline{c}) - \pi_{sc}(q^* | \overline{TR}, \overline{c})] \tag{23}$$

Because $0 < \Phi_i^{RS} < 1$, with this type of investment, $\triangle \pi_i^{RS} > 0$ when $\triangle \pi_{sc} > 0$, $i = 1,2,\ldots,n$. Consequently, member $i$ is willing to improve his reliability with this investment when the total profit of the supply chain increases. With the same approach, we can show that under the RSR contracts, the added cost is shared by all members, and the total profit equals the profit under the RS contract.

However, it is difficult to add the second type of investment into the unit production cost. We refer to this type of cost as the development cost. For example, one supplier could employ a research group to design a more reliable component or production process. If all members share this cost, then they must monitor the cost, a process that is difficult and costly in real-life practice. In Hollywood, for example, profit-sharing contracts are used, under which the members share the final profit of the supply chain. However, litigation about profit-sharing contracts is widely reported because the costs of some members cannot be agreed upon by other members (Weinstein, 1998). Therefore, in the real world, the development cost is usually not shared. Let $TC_i^D$ be the development cost of member $i$ to improve his reliability. For simplicity, we assume that $c_i$ is not influenced by this type of improvement. The expected increased profit of the supply chain is

$$\Delta\pi_{sc} = \pi_{sc}(q^* | \overline{TR} + \Delta\overline{TR}, \overline{c}) - \pi_{sc}(q^* | \overline{TR}, \overline{c}) - TC_i^D \tag{24}$$

If $\triangle \pi_{sc} \le 0$, the development cannot increase the total profit. Hereafter we only consider the cases where $\triangle \pi_{sc} > 0$. Under the RS contract, the expected increased profit of member $i$ who implements the development is

$$\Delta\pi_i^{RS} = \Phi_i^{RS} [\pi_{sc}(q^* | \overline{TR} + \Delta\overline{TR}, \overline{c}) - \pi_{sc}(q^* | \overline{TR}, \overline{c})] - TC_i^D \tag{25}$$

The expected increased profits of other members who do not implement the development are

$$\Delta\pi_j^{RS} = \Phi_j^{RS} [\pi_{sc}(q^* | \overline{TR} + \Delta\overline{TR}, \overline{c}) - \pi_{sc}(q^* | \overline{TR}, \overline{c})] \quad j = 1,2,\ldots,n \text{ and } j \ne i \tag{26}$$

**Theorem 4.** *Considering the development cost, there exist some cases in which the RS contract cannot achieve the maximum total profit.*

**Proof of Theorem 4.** It is easy to prove that, given a fixed $TC_i^D$, the optimal total profit of the supply chain increases with the reliability of the members. Consequently, we can infer that $\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})-\pi_{sc}(q^*|\overline{TR},\overline{c})>0$, when $\Delta\overline{TR}>\mathbf{0}$. Because $0<\Phi_i^{RS}<1$, from Eqs. it can be inferred that $\triangle\pi_{sc}>\triangle\pi_i^{RS}$. Therefore, given any $\Delta\overline{TR}>\mathbf{0}$, there exist $TC_i^D$ that satisfy $\triangle\pi_i^{RS}<0<\triangle\pi_{sc}$. In these cases, member $i$ will not increase the reliability and the largest total profit of the supply chain is not achieved. □

Let $\triangle\Phi_i^0$ and $\alpha^0$ be the $\triangle\Phi_i$ and $\alpha$ under an original RSR contract setting when the reliability of member $i$ is not improved; let $\triangle\Phi_i^t$ and $\alpha^t$ be the $\triangle\Phi_i$ and $\alpha$ when member $i$ increases his reliability. The expected increased profit of member $i$ is

$$\Delta\pi_i^{RSR}=(\Phi_{F\_i}+\Delta\Phi_i^t)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})-\left(\Phi_{F\_i}+\Delta\Phi_i^0\right)\pi_{sc}(q^*|\overline{TR},\overline{c})-TC_i^D \tag{27}$$

If we use $\Phi_i^{RS}$ under the RS contract as $\Phi_{F\_i}$, from Eqs. (25) and (27), we obtain that

$$\Delta\pi_i^{RSR}-\Delta\pi_i^{RS}=\Delta\Phi_i^t\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})-\Delta\Phi_i^0\pi_{sc}(q^*|\overline{TR},\overline{c}) \tag{28}$$

where $\Delta\Phi_i^0=\alpha^0(TR_i-TR_{av})$ and $\Delta\Phi_i^t=\alpha^t(TR_i+\Delta TR_i-TR_{av}-\Delta TR_i/n)$.

Then,

$$\Delta\pi_i^{RSR}-\Delta\pi_i^{RS}=\alpha^t(TR_i+\Delta TR_i-TR_{av}-\Delta TR_i/n)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})-\alpha^0(TR_i-TR_{av})\pi_{sc}(q^*|\overline{TR},\overline{c}) \tag{29}$$

Because $TR_i+\triangle TR_i-TR_{av}-\triangle TR_i/n>TR_i-TR_{av}$ when $\triangle TR_i>0$, we discuss the profit increase of member $i$ under an RSR contract in three cases.

Case 1. $TR_i-TR_{av}\le 0$ and $TR_i+\triangle TR_i-TR_{av}-\triangle TR_i/n\ge 0$. In this case, $TR_i$ is smaller than or equal to the average reliability before member $i$ improves his reliability, while $TR_i+\triangle TR_i$ is larger than or equal to the new average reliability.

Case 2. $TR_i-TR_{av}<0$ and $TR_i+\triangle TR_i-TR_{av}-\triangle TR_i/n<0$. In this case, the reliability of member $i$ is smaller than the average reliability after he improves his reliability. Hence, it can be inferred that $TR_i-TR_{av}<0$ with $\triangle TR_i>0$.

Case 3. $TR_i-TR_{av}>0$. In this case, $TR_i$ is larger than the average reliability before member $i$ improves his reliability. Thus, it can be inferred that $TR_i+\triangle TR_i-TR_{av}-\triangle TR_i/n>0$ with $\triangle TR_i>0$.

Let $\alpha_i^0$ and $\alpha_i^t$ be the values of $\alpha_i$ under the original and the new reliability scenarios, respectively, $i=1,2,\ldots,n$.

**Theorem 5.** *Given $\triangle TR_i>0$, the following applies*: (i) *in* Case 1, *given any $\alpha^0$ where both $\alpha^0$ and $TR_i+\triangle TR_i-TR_{av}-\triangle TR_i/n$ are not zero simultaneously, we can always find a feasible $\alpha^t$ so that $\triangle\pi_i^{RSR}-\triangle\pi_i^{RS}>0$*; (ii) *in* Case 2, *given any $\alpha^0\neq 0$, we can always find a feasible $\alpha^t$ so that $\triangle\pi_i^{RSR}-\triangle\pi_i^{RS}>0$*; (iii) *in* Case 3, *the RSR contract can find an $\alpha^t$ that makes $\triangle\pi_i^{RSR}-\triangle\pi_i^{RS}>0$ if and only if*

$$\alpha^0<\frac{(TR_i+\Delta TR_i-TR_{av}-\Delta TR_i/n)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})}{(TR_i-TR_{av})\pi_{sc}(q^*|\overline{TR},\overline{c})}\min\{\alpha_1^t,\ldots,\alpha_n^t\} \tag{30}$$

**Proof of Theorem 5.**

(i) In Case 1, $TR_i-TR_{av}\le 0$ and $TR_i+\triangle TR_i-TR_{av}-\triangle TR_i/n\ge 0$. Noting that $\alpha^0$, $\alpha^t\ge 0$, we can obtain that $\triangle\Phi_i^0=\alpha^0(TR_i-TR_{av})\le 0$ and $\triangle\Phi_i^t=\alpha^t(TR_i+\triangle TR_i-TR_{av}-\triangle TR_i/n)\ge 0$. Because $TR_i+\triangle TR_i-TR_{av}-\triangle TR_i/n$ and $TR_i-TR_{av}$ cannot be zero simultaneously, given any $\alpha^0$ where both $\alpha^0$ and $TR_i+\triangle TR_i-TR_{av}-\triangle TR_i/n$ are not zero simultaneously, we can always find a feasible $\alpha^t$ so that $\triangle\pi_i^{RSR}-\triangle\pi_i^{RS}>0$.

(ii) In Case 2, $TR_i-TR_{av}<0$ and $TR_i+\triangle TR_i-TR_{av}-\triangle TR_i/n<0$. Noting that $\alpha^0$, $\alpha^t\ge 0$, we can infer that $\triangle\pi_i^{RSR}-\triangle\pi_i^{RS}>0$ when

$$\alpha^t<\frac{(TR_{av}-TR_i)\pi_{sc}(q^*|\overline{TR},\overline{c})}{(TR_{av}+\Delta TR_i/n-TR_i-\Delta TR_i)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})}\alpha^0 \tag{31}$$

Because

$$\frac{(TR_{av}-TR_i)\pi_{sc}(q^*|\overline{TR},\overline{c})}{(TR_{av}+\Delta TR_i/n-TR_i-\Delta TR_i)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})}>0$$

and $\alpha^t$ is restricted to the range of [0, $\min\{\alpha_1^t,\ldots,\alpha_n^t\}$), given any $\alpha^0\neq 0$, we can always find an $\alpha^t$ that satisfies Inequality (31), and $\triangle\pi_i^{RSR}-\triangle\pi_i^{RS}>0$ is achieved.

(iii) In Case 3, $TR_i-TR_{av}>0$. Suppose that, before the reliability is improved, there are $m$ members whose reliability levels are lower than the average level. When member $i$ increases his reliability by $\triangle TR_i>0$, the average reliability is increased by $\triangle TR_i/n$. Let $VR_j^t$ be $TR_j-TR_{av}-\triangle TR_i/n$ and suppose that there are $l$ members with a negative $VR_j^t$. Then, we can infer that $l\ge m$. For the $m$ members with negative $VR_j$ under the original reliability scenario, $\alpha_j^t=L_{\triangle\Phi j}/VR_j^t=L_{\triangle\Phi j}/(TR_j-TR_{av}-\triangle TR_i/n)<L_{\triangle\Phi j}/(TR_j-TR_{av})=\alpha_j^0$, where $(TR_j-TR_{av}-\triangle TR_i/n)<(TR_j-TR_{av})<0$. Therefore, we infer that $\min\{\alpha_1^t,\ldots,\alpha_n^t\}<\min\{\alpha_1^0,\ldots,\alpha_n^0\}$.

Considering Eq. (29), to achieve $\triangle\pi_i^{RSR}-\triangle\pi_i^{RS}>0$, $\alpha^0$ and $\alpha^t$ should satisfy

$$\frac{\alpha^t}{\alpha^0}>\frac{(TR_i-TR_{av})\pi_{sc}(q^*|\overline{TR},\overline{c})}{(TR_i+\Delta TR_i-TR_{av}-\Delta TR_i/n)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})} \tag{32}$$

If

$$\alpha^0<\frac{(TR_i+\Delta TR_i-TR_{av}-\Delta TR_i/n)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})}{(TR_i-TR_{av})\pi_{sc}(q^*|\overline{TR},\overline{c})}\min\{\alpha_1^t,\ldots,\alpha_n^t\}$$

then we can always find an $\alpha^t$ within the range of

$$\left(\frac{(TR_i-TR_{av})\pi_{sc}(q^*|\overline{TR},\overline{c})}{(TR_i+\Delta TR_i-TR_{av}-\Delta TR_i/n)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})}\alpha^0,\min\{\alpha_1^t,\ldots,\alpha_n^t\}\right)$$

that satisfies Inequality (32). Therefore, we can always find an $\alpha^t$ that makes $\Delta\pi_i^{RSR}-\Delta\pi_i^{RS}>0$ and that is smaller than $\min\{\alpha_1^t,\ldots,\alpha_n^t\}$.

If

$$\alpha^0\ge\frac{(TR_i+\Delta TR_i-TR_{av}-\Delta TR_i/n)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})}{(TR_i-TR_{av})\pi_{sc}(q^*|\overline{TR},\overline{c})}\min\{\alpha_1^t,\ldots,\alpha_n^t\}$$

then any $\alpha^t$ that satisfies Inequality (32) is larger than or equal to $\min\{\alpha_1^t,\ldots,\alpha_n^t\}$. In this case, there will be no feasible $\alpha^t$. □

From the proof of Theorem 5, we can see that $\min\{\alpha_1^t,\ldots,\alpha_n^t\}<\min\{\alpha_1^0,\ldots,\alpha_n^0\}$ and it is possible that

$$\frac{(TR_i+\Delta TR_i-TR_{av}-\Delta TR_i/n)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})}{(TR_i-TR_{av})\pi_{sc}(q^*|\overline{TR},\overline{c})}\min\{\alpha_1^t,\ldots,\alpha_n^t\}<\min\{\alpha_1^0,\ldots,\alpha_n^0\} \tag{33}$$

In this case, we cannot arbitrarily select an $\alpha^0$ between 0 and $\min\{\alpha_1^0,\ldots,\alpha_n^0\}$.

Fig. 2 shows the possible sets of ($\alpha^0$, $\alpha^t$). Let $\alpha_Y^0$ and $\alpha_Z^0$ be $\alpha^0$ at Points $Y$ and $Z$ wherein

$$\alpha_Y^0<\frac{(TR_i+\Delta TR_i-TR_{av}-\Delta TR_i/n)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})}{(TR_i-TR_{av})\pi_{sc}(q^*|\overline{TR},\overline{c})}\min\{\alpha_1^t,\ldots,\alpha_n^t\}$$

and

$$\alpha_Z^0 > \frac{(TR_i+\Delta TR_i-TR_{av}-\Delta TR_i/n)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})}{(TR_i-TR_{av})\pi_{sc}(q^*|\overline{TR},\overline{c})}\min\{\alpha_1^t,\ldots,\alpha_n^t\}$$

when $\alpha^0=\alpha_Y^0$, there are feasible values of $\alpha^t$ between Points $U$ and $V$ that satisfy the constraint and make $\Delta\pi_i^{RSR}-\Delta\pi_i^{RS}>0$. However, when $\alpha^0=\alpha_Z^0$, there is no feasible $\alpha^t$ that satisfies $\Delta\Phi_i^t>L_{\Delta\Phi i}$ and makes $\Delta\pi_i^{RSR}-\Delta\pi_i^{RS}>0$ simultaneously.

**Theorem 6.** *There exist some cases in which the RSR contract can bring a larger total profit than the RS contract.*

**Proof of Theorem 6.** According to the proof of Theorem 4, given any $\Delta\overline{TR}>\mathbf{0}$, there exist $TC_i^D$ that satisfy $_\Delta\pi_i^{RS}<0<\triangle\pi_{sc}$, when the largest total profit of the supply chain is not achieved under the RS contract. From the discussion and the proof of Theorem 5, we can see that the RSR contract can always achieve $\triangle\pi_i^{RSR}-\triangle\pi_i^{RS}>0$ for member $i$, who improves his reliability. Therefore, given any $\Delta\overline{TR}>\mathbf{0}$, there exist $TC_i^D$ that satisfy

$$\begin{cases}\Delta\pi_{sc}=\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})-\pi_{sc}(q^*|\overline{TR},\overline{c})-TC_i^D>0\\ \Delta\pi_i^{RS}=\Phi_i^{RS}[\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},\overline{c})-\pi_{sc}(q^*|\overline{TR},\overline{c})]-TC_i^D<0\\ \Delta\pi_i^{RSR}=(\Phi_{Fi}+\Delta\Phi_i^t)\pi_{sc}(q^*|\overline{TR}+\Delta\overline{TR},,\overline{c})-(\Phi_{Fi}+\Delta\Phi_i^0)\pi_{sc}(q^*|\overline{TR},\overline{c})-TC_i^D>0\end{cases} \tag{34}$$

In this case, the expected total profit of the supply chain is increased with the reliability improvement. Under the RS contract, member $i$ will not implement the reliability improvement that is implemented under the RSR contract. Then, the RSR contract creates a larger total profit for the supply chain than the RS contract. □

In real-life practice, it is common for the managers to improve members' reliability by using the development cost. Then, there is a cost–benefit trade-off satisfied by the managers. The incentives that the RS contract provides to coordinate the members' quantity decisions distort the investment decisions. A similar phenomenon occurs in the newsvendor problem with effort-dependent demand (e.g., see Cachon and Lariviere, 2005). Under the same reliability increment, the RSR contract can support a greater development cost than can the RS contract. Therefore, the RSR contract generates a larger total profit when the development cost is restricted to certain ranges. Some members' profits decrease during the second round when $\triangle\Phi_j<0$. Nevertheless, it is possible for all members to obtain larger profits than with the RS contract because the RSR contract makes possible a larger total profit. When the total profit of the supply chain under the RSR contract is larger, we can set the profit threshold of member $j$ to equal the profit under the RS contract, with $j=1,2,\ldots,n$. In this case, all members can obtain a larger profit than under the RS contract, despite $\triangle\Phi_j<0$ for some members. This scenario will be demonstrated by the numerical experiments in the next section.

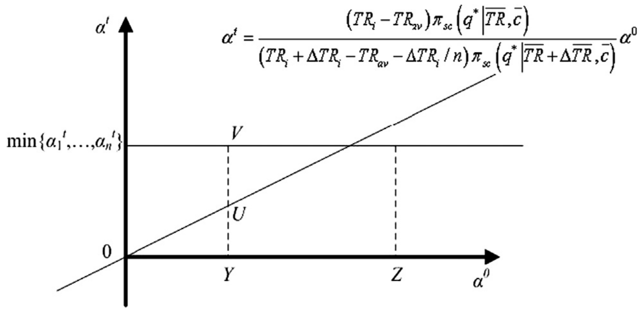


**Fig. 2.** Feasible sets of $(\alpha^0, \alpha^t)$ under the RSR contract.

## 4. Numerical experiments

In this section, we clarify the proposed RSR contracts using numerical experiments. Suppose that there are four members in the supply chain, as shown in Fig. 3. In this supply chain, Members 3 and 4 supply two types of material to Member 2, which produces one final product, and the retailer sells it to customers.

Assume that $X$ follows a normal distribution with a mean of 1000 and a standard deviation of 300. The original reliability levels of the members are 0.94, 0.95, 0.81, and 0.96, respectively. Based on the results in Section 2, the expected revenue of the retailer is

$$R(q)=p\left(\int_0^{0.94q}xf(x)\right)dx+\int_{0.94q}^{\infty}0.94qf(x)dx)\\ +s\int_0^{0.94q}(0.94q-x)f(x)dx \tag{35}$$

The retail price is \$30, and the salvage value is \$1. Other assumed problem data are introduced in Table 1.

In a conventional market setting, the supply chain works as follows. Based on Eq.(36), the retailer places an order for $q_M$ units of the final products. In turn, the manufacturer orders the components from the suppliers at the unit wholesale price $\omega_{M\_3}$ and $\omega_{M\_4}$. Let $\pi_{M\_i}$ and $\pi_{M\_sc}$ be the profits of member $i$ and the supply chain in the conventional market setting. The profits of the four members in the conventional market setting are

$$\pi_{M\_1}=R(q_M)-(c_1+\omega_{M\_2})q_M \tag{36}$$

$$\pi_{M\_2}=\omega_{M\_2}q_M-(c_2+\omega_{M\_3}+\omega_{M\_4})q_M/TR_2 \tag{37}$$

$$\pi_{M\_3}=\omega_{M\_3}q_M/TR_2-c_3q_M/(TR_2TR_3) \tag{38}$$

$$\pi_{M\_4}=\omega_{M\_4}q_M/TR_2-c_4q_M/(TR_2TR_4) \tag{39}$$

By setting $\omega_{M\_2}$ in Eq. (36) to \$20.5, we can ascertain that the optimal order quantity of the retailer in the traditional market setting is 863 and the expected total profit, $\pi_{M\_sc}$, is \$15,905.0. The expected profits in the conventional market setting are shown in Table 2. The optimal order quantity of the supply chain under the current reliability levels is 1264, and the expected total profit, $\pi_{sc}(q^*)$, is \$18,482.9. Giannoccaro and Ponatrandolfo (2004) claimed that the contracts could be desirable if all of the members obtain larger profits than in the conventional market setting. Hence, if the supply chain switches from a conventional market setting to the RS or RSR contracts, the profit thresholds are the profits of the members in the conventional market setting, i.e.,

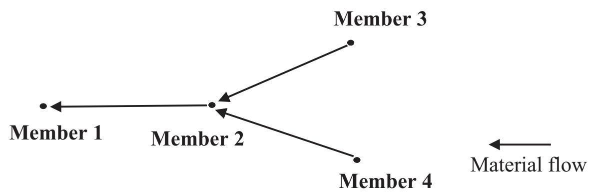


**Fig. 3.** A supply chain with four members.

**Table 1**
Problem data.

| Member | Unit production cost (\$) | Price in the conventional market setting (\$) |
|---|---|---|
| 1 | 0.5 | |
| 2 | 0.6 | 20.5 |
| 3 | 2.7 | 10.0 |
| 4 | 3.2 | 5.5 |

$\pi_{T\_i}=\pi_{M\_i}$. In addition, if we set $\Phi_i^{RS}=\pi_{M\_i}/\pi_{M\_sc}$, then the RS contract can bring larger profits to all of the members. For the sake of simplicity, we present only our analysis of the profits when $\Phi_{F\_i}=\Phi_i^{RS}=\pi_{M\_i}/\pi_{M\_sc}$, $i=1,2,3,4$. From Eq. (18), we have ( $L_{\triangle\Phi 1}$, $L_{\triangle\Phi 2}$, $L_{\triangle\Phi 3}$, $L_{\triangle\Phi 4}$)=(−4.220%,−2.691%,−5.314%,−1.721%).

Table 3 shows the results that were obtained from using the *APA* method. The symbol "/" means that we do not need to consider the value for that location in the table. In this experiment, we use 100 as the large number.

Based on the reliability levels of the four members, we determine that the average reliability is 0.915. Because only $VR_3$ is less than zero, $\min\{\alpha_1,\alpha_2,\alpha_3,\alpha_4\}=\alpha_3=0.5061$. Consequently, $\alpha$ can be any value between 0 and 0.5061. In Table 3, $\alpha=0.5061$ is used as an extreme case, and $\triangle\Phi_3=L_{\triangle\Phi 3}=-5.314\%$. Table 4 presents the profits under the RS contract and the RSR contract with different values of $\alpha$. When $\alpha=0.5061$, Member 3′s profit under the RSR contract is identical to his profit in the conventional market setting.

As discussed before, there are three cases in which the members improve their reliability with the development cost. For the sake of simplicity, we present only our analysis of Case 1 because the supply chain can usually increase the total profit more significantly by improving the reliability of the member with the lowest reliability. The analysis for the other cases is similar. Suppose Member 3′s development cost function is

$$TC_3^D(TR_3^t)=\begin{cases} A+e^{k(TR_3^t-TR_3^o)/(TR_3^{max}-TR_3^t)} & TR_3^o<TR_3^t\le TR_3^{max} \\ 0 & TR_3^t\le TR_3^o \end{cases} \quad (40)$$

where $TR_3^t(=TR_3^o+\Delta TR_3)$ is the target reliability of Member 3. $TR_3^o$ and $TR_3^{max}$ signify the original reliability and the maximum reliability of Member 3, respectively. $A$ is the fixed cost, and $k$ represents the difficulties in improving reliability that are determined by such factors as the design complexity and technological limitations. This function is widely used in studies of imperfect production-inventory systems (e.g., see Sarkar, 2012; Sana, 2010). In this experiment, $TR_3^o=0.81$, and we let $A=\$290$, $k=1/14$, and $TR_3^{max}=0.985$. It can be shown that the optimal $TR_3^t$ that maximizes the supply chain's profit is 0.98, and $TC_3^D(0.98)=\$301.3$. The optimal order quantity is 1287 units and the supply chain's profit is \$18,959.9(=19,261.2–301.3). Under the RS contract, if Member 3 improves his reliability, the largest profit of Member 3 is \$7035.9 (when $TR_3^t=0.978$) that is smaller than the profit before improving his reliability (\$7038.3). Consequently, Member 3 will not improve his reliability, and the supply chain's profit under the RS contract is still \$18,482.9. To compare our RSR contract with the RS contract, we assume the same supply chain switches from the RS contract to the RSR contract. Then, the profit thresholds of the members are the profits under the RS contract, i.e., $\pi_{T\_i}$ is the profit under the RS contract shown in Table 4. We can obtain the results obtained from the *APA* method when Member 3 increases his reliability to 0.98, as Table 5 shows.

Under the new reliability scenario, $\alpha^t$ is restricted to the range of [0, 0.698). Based on Theorem 5, the RSR contracts with any $\alpha^0$ and $\alpha^t$ obtained from the *APA* method can bring a larger increased profit for Member 3 than the RS contract. We take $\alpha^0=0.05$ and $\alpha^t=0.25$ as an example, and the result is shown in Table 6.

Table 6 shows the profits of all of the members and the supply chain under the RS contract and the RSR contract. Clearly, the RSR contract achieves larger profits for all of the members compared to the RS contract. As mentioned in Section 3, the members whose reliability levels are higher than the average level can obtain higher profits when the value of $\alpha^t$ is higher. On the other hand, the members whose reliability levels are lower than the average level will lose more profits when the value of $\alpha^t$ is higher. If we set $\alpha^t=0.698$, then Member 1 will obtain the same profit as the profit under the RS contract.

## 5. Managerial implications and conclusions

This paper analyzes the coordination of an N-stage supply chain while accounting for member reliability. An N-stage supply chain

**Table 2**
Expected profits in the conventional market setting.

| Member | 1 | 2 | 3 | 4 | Supply chain |
|---|---|---|---|---|---|
| Profit (\$) | 4814.7 | 3066.0 | 6056.1 | 1968.2 | 15,905.0 |
| $\Phi_i$ (%) | 30.27 | 19.28 | 38.08 | 12.37 | 100 |

**Table 3**
Results of the *APA* method.

| Member | $TR_i$ | $VR_i$ | $L_{\triangle\Phi i}$ (%) | $\alpha_i$ | $\triangle\Phi_i$ (%) |
|---|---|---|---|---|---|
| 1 | 0.94 | 0.025 | / | 100 | 1.265 |
| 2 | 0.95 | 0.035 | / | 100 | 1.771 |
| 3 | 0.81 | −0.105 | −5.314 | 0.5061 | −5.314 |
| 4 | 0.96 | 0.045 | / | 100 | 2.278 |

**Table 4**
Expected profits under different contracts.

| Member | Profit (\$) | | | | |
|---|---|---|---|---|---|
| | Conventional market setting | RS contract | RSR contract | | |
| | | | $\alpha=0.0500$ | $\alpha=0.2500$ | $\alpha=0.5061$ |
| 1 | 4814.7 | 5594.8 | 5617.9 | 5710.3 | 5828.6 |
| 2 | 3066.0 | 3563.5 | 3595.8 | 3725.2 | 3890.9 |
| 3 | 6056.1 | 7038.3 | 6941.3 | 6553.1 | 6056.1 |
| 4 | 1968.2 | 2286.3 | 2327.9 | 2494.3 | 2707.3 |
| Supply chain | 15,905.0 | 18,482.9 | 18,482.9 | 18,482.9 | 18,482.9 |

**Table 5**
Results of the *APA* method under the new reliability scenario.

| Member | $TR_i$ | $VR_i$ | $L_{\triangle\Phi i}$ (%) | $\alpha_i$ |
|---|---|---|---|---|
| 1 | 0.94 | −0.0175 | −1.223 | 0.698 |
| 2 | 0.95 | −0.0075 | −0.779 | 1.038 |
| 3 | 0.98 | 0.0225 | / | 100 |
| 4 | 0.96 | 0.0025 | / | 100 |

**Table 6**
Comparison of profits under the RS and RSR contracts.

| Member | Profit (\$) | | | | |
|---|---|---|---|---|---|
| | RS contract | RSR contract | | $\triangle\pi_i^{RSR}$ | $\pi_i^{RSR}-\pi_i^{RS}$ |
| | | $\alpha^0=0.05$ | $\alpha^t=0.25$ | | |
| 1 | 5594.8 | 5617.9 | 5746.1 | 128.2 | 151.3 |
| 2 | 3563.5 | 3595.8 | 3677.4 | 81.6 | 113.9 |
| 3 | 7038.3 | 6941.3 | 7141.7 | 200.4 | 103.4 |
| 4 | 2286.3 | 2327.9 | 2394.7 | 66.8 | 108.4 |
| Supply chain | 18,482.9 | 18,482.9 | 18,959.9 | 477.0 | 477.0 |

comprises more than two stages, and each member could face more than one direct upstream member. Reliability is included in our supply chain model. This type of supply chain is common in the real world and has a more general structure than is discussed by current studies. We have proposed an RSR contract that can achieve supply chain coordination and can allocate the total profit among the members arbitrarily. A two-round profit allocation mechanism is used. The managers can easily see the relationship between the final profits, the wholesale prices, the shared revenue, and the reliability. We have noted that competitive RSR contracts should (i) create a larger total profit for the supply chain than the RS contract; and (ii) create higher profits for all of their members compared to their own profit thresholds alone. It is shown that the RSR contract can coordinate the supply chain and support any meaningful set of profit thresholds.

Next, we have proposed an *APA* method for adjusting the profit allocation under the RSR contract. With the *APA* method, the members have a greater incentive to implement reliability improvement than under the RS contract, and all of their profit thresholds are satisfied. We have also noted that, even though there could be many methods for allocating the profit based on the reliability, the *APA* method is competitive for the following three reasons: (i) the *APA* method can be used to arbitrarily adjust the profit based on the reliability; (ii) the *APA* method can be used separately for different groups of members; and (iii) the *APA* method is independent of the reliability evaluation approach. Using the *APA* method, we can group members based on their characteristics in terms of their reliability and use the *APA* method separately with each group. Because the *APA* method is independent of the reliability evaluation approach, different supply chains or groups can be analyzed using different reliability evaluation models. Therefore, the profits can be independently adjusted for each group, and supply chain coordination can still be achieved. This finding means that, given any set of reliability values, the *APA* method can be used to adjust profits and increase the compatibility of our RSR contract with real-world supply chain needs.

We discuss how the improvement investment influences the profits under different contracts. We show that, when the investment cost of the member can be shared by other supply chain members, he can obtain larger profits under the RS and RSR contracts by improving the reliability. In this case, the RS and RSR contracts achieve the same total profit of the supply chain. On the other hand, it is common in real life practice that the investment (development) cost cannot be shared by other members. It is found that there exist some cases for which the members refuse to improve the reliability under the RS contract, and the supply chain fails to obtain the maximum total profit. We discuss the reliability improvement in three cases. If the reliability is lower than the average level before improvement, then it is more flexible to set $\alpha^0$ and $\alpha^t$ to values that encourage the member to implement the improvement. Then, given any set of profit thresholds, the RSR contract can bring a larger total profit than the RS contract. This scenario means that the RSR contract is feasible and flexible. Our results can serve as guidelines for managers who seek to set the decision variables appropriately for achieving a larger total profit under the RSR contract.

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