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Supply chain coordination under budget constraints

Xuehao Feng [a], Ilkyeong Moon [b,*], Kwangyeol Ryu [c]

[a] Ocean College, Zhejiang University, Hangzhou 310058, China
[b] Department of Industrial Engineering, Seoul National University, Seoul 151-744, Republic of Korea
[c] Department of Industrial Engineering, Pusan National University, Busan 609-735, Republic of Korea

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ABSTRACT

Budget constraints are commonly considered in real decision frameworks; however, the literature has rarely addressed the design of contracts for supply chains with budget-constrained members and in which capital costs are considered. In this article, we study supply chain coordination of budget-constrained members when a financial market is unavailable. We propose a revenue-sharing-and-buy-back (RSBB) contract that combines revenue-sharing (RS) and buy-back (BB) contracts. We compare the performance of RS, BB, and RSBB contracts under a coordinated two-stage supply chain in which members experience budget constraints. Results show that the RS and BB contracts are not feasible under certain budget scenarios, whereas the RSBB contract can always be used to coordinate the supply chain and arbitrarily divide profits. We propose a profit allocation approach to address information symmetry created by undisclosed budget thresholds. Our analytical and numerical results provide insight into how managers select an appropriate contract based on their budget scenarios and capital costs.

1. Introduction

In existing studies on supply chain contracts, it has been commonly assumed that all of the supply chain members have infinite budgets. Under this assumption applied to a conventional market setting, the retailer orders fewer products than the channel-wide optimal quantity (Spengler, 1950). In developed economies, such as those in the United States or the European Union, a powerful supplier (or retailer) has enough access to the financial market to obtain a sufficient budget. However, in many developing countries that do not have an advanced financial market, supply chain members, even the most powerful, may be unable to obtain sufficient money to order optimal quantities. In these cases, supply chain managers must make decisions under strict budget constraints such that they order fewer products than the channel-wide optimal quantity. The motivation for considering absolute budget constraints is illustrated by examples from China.

Li Jun Orchard (LJO) plants and supplies peaches and watermelons to retailers in Beijing. The retailers pay a deposit when sending orders to LJO and pay the balance when they receive the products. LJO cannot obtain bank loans because fruit growing is a high-risk industry that can be significantly influenced by natural disasters, and the company does not have the cash flow to satisfy bank requirements. In another example, from Moon, Feng, and Ryu (2015), an electronics distributor in China cannot secure a bank loan because neither its fixed assets nor cash flow amounts satisfy financing requirements. The managers of LJO and the electronics distributor must make decisions under absolute budget constraints.

Many companies with budget constraints attempt to improve their financial management. A survey of more than 170 firms showed that 39% of small companies were inhibited from maximizing their global trade opportunities by the costly and complex proof of financial stability for conducting an imports/export operation (Enslow, 2006). However, to the best of our knowledge, most of the contracts studied have been used to achieve supply chain coordination under the assumption that the members have sufficient budgets to make a range of decisions.

Some studies have focused on budget constraints by firms that can secure loans from a financial market, but do not address supply chain coordination. For example, Dada and Hu (2008) discussed a supply chain model in which budget-constrained retailers can borrow funds from a bank. Caldentey and Haugh (2009) proposed a contract through which a budget-constrained retailer can hedge its budget constraint in the financial market. Chen and Cai (2011) studied a supply chain model in which a budget-constrained retailer can borrow funds from a bank or logistics firm. The literature describes situations in which the financial market loans money to the budget-constrained members and joins into finance

* Corresponding author. Tel.: +82 2 880 7151; fax: +82 2 889 8560.
E-mail address: ikmoon@snu.ac.kr (I. Moon).

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contracts, an efficient approach if the borrowers can satisfy the requirements of the financial market and if the negotiation is not costly. However, especially for those with small companies, some supply chains may find involving the financial market an infeasible or inefficient option. First, the financial market may be unavailable to small companies, which usually do not have high credit ratings. Second, involving the financial market may create new contract parameters, such as specifications for an interest rate that depends on the members' default risk (e.g., Dada & Hu, 2008; Lee & Rhee, 2010). In this case, all of the supply chain members and those in the financial market must agree to the parameters, which can lead to a costly negotiation process (Moon et al., 2015). Consequently, it is important to study the coordination of supply chains with budget-constrained members for whom the financial market is unavailable.

Contracts have been popular for coordinating supply chains. The buy-back (BB) contract was first studied by Pasternack (1985). Under a BB contract, the manufacturer charges the retailer a unit wholesale price and pays the retailer a buyback price per unit unsold. Cachon and Lariviere (2005) proposed a revenue-sharing (RS) contract, under which the manufacturer charges the retailer a unit wholesale price and shares a proportion of the retailer's total revenue. RS contracts have also been extended to coordinate supply chains with more than two members (e.g., Jiang, Wang, & Yan, 2014). See Hou, Zeng, and Zhao (2010) and Feng, Moon, and Ryu (2014) for detailed surveys on BB and RS contracts. Recently, Nosoohi and Nookabadi (2014) developed an option contract for coordinating a manufacturer and its component supplier. Arya, Löffler, Mittendorf, and Pfeiffer (2015) discussed simple cost-based contracts with a middleman for supply chain coordination. Several composite contracts have been developed for new supply chain problems (Chen, 2011; Jörnsten, Nonås, Sandal, & Ubøe, 2013; Taylor, 2002; Wang & Webster, 2007; Xiong, Chen, & Xie, 2011). Each of these composite contracts consists of two subcontracts. All of these studies focused on supply chain coordination with members operating without budget constraints.

Yan and Sun (2013) designed a wholesale-price contract and a finite loan scheme to coordinate supply chains with a manufacturer, a capital-constrained retailer, and a bank. Jing and Seidmann (2014) compared banks and trade credit in a supply chain with a supplier and a budget-constrained retailer. Xu, Cheng, and Sun (2015) discussed the performance of RS, output-penalty, and cost-sharing contracts for coordinating outsourcing supply chains with firms under financial constraints. Jin, Wang, and Hu (2015) analyzed contract type under sales promotion in supply chain coordination with a capital-constrained retailer. These studies assumed that the manufacturer (or supplier) has a sufficient budget. Moon et al. (2015) extended the RS contract for multi-echelon supply chains with budget-constrained members. However, they assumed that the terminal members have sufficient budgets.

Lee and Rhee (2010) studied the performance of RS and BB contracts when the budget-constrained retailer and supplier can borrow as much money as needed from the financial market. Our paper differs from that work in meaningful ways. First, Lee and Rhee (2010) assumed that both retailer and manufacturer must expend their internal budgets, while we study more general budget constraints. Second, we propose a new contract to achieve supply chain coordination without a financial market. The absence of a financial market could influence supply chain coordination more significantly when only one member is budget constrained. Third, Lee and Rhee (2010) studied a special case of open-account financing in which the retailer pays the remainder after the total sales revenue was obtained. However, in practice, the due date for the retailer to pay the remainder is often set before the sales revenue is collected by the retailer. Delaying the due date may require a new negotiation process and additional administrative costs. In this paper, we study open-account financing in which the due date is set before the retailer obtains the sales revenue as is common practice.

The current RS and BB contracts have limitations. First, RS contracts may necessitate additional costs for the manufacturer who must monitor the retailer's revenue (Cachon & Lariviere, 2005). Consequently, RS contracts can be unfair to the manufacturer. Second, when capital costs are considered, BB contracts also can be unfair to the retailer. Under the BB contract, the wholesale price can be high when the sales price is high or when the profit percentage for the retailer is low. Third, under budget constraints, RS and BB contracts may not allow for supply chain coordination. However, a composite contract consisting of revenue-sharing and buy-back mechanisms may overcome the limitations. We propose a revenue-sharing-and-buy-back (RSBB) contract, which combines RS and BB contracts.

We consider a two-stage supply chain that consists of a retailer and a manufacturer who have budget constraints. This paper contributes to the literature in three ways. First, we analyze supply chain coordination with budget-constrained members when the financial market is unavailable. Second, we propose a flexible contract for supply chain coordination under budget constraints. Third, we show the limitation of RS and BB contracts under budget constraints.

The paper is organized as follows. Section 2 analyzes the decision framework of a supply chain under budget constraints and proposes the RSBB contract. Section 3 discusses three regions of the budget space in which the RS, BB, and RSBB contracts show different performance. Section 4 presents numerical experiments and related discussions. We provide concluding remarks and suggest future avenues for our model in Section 5.

2. The revenue-sharing-and-buy-back contract

2.1. Supply chain model

We consider a supply chain consisting of a retailer (r) and a manufacturer (m). Both members are risk neutral and the retailer faces a newsvendor problem. The uncertain customer demand is represented by the nonnegative random variable D defined over the continuous interval $[0, \infty)$. Unit production costs for the retailer and the manufacturer are c_r and c_m, respectively. Let $c = c_r + c_m$. The retailer sells the products to customers at a retail price, $p(> c)$. The unsold products are salvaged by the retailer with a unit salvage value, s. We take the above parameters as exogenously specified. The retailer decides the order quantity, $q(\geqslant 0)$, and pays the manufacturer a wholesale price, w, for each unit purchased. Before the manufacturer begins production, the retailer pays a proportion of the total trading amount up front as a deposit. The retailer pays the rest of the total amount after a fixed period (e.g., 30 days) that ends before the final sales revenue is obtained. This scheme reflects a typical form of open-account financing that has become popular in recent years. For simplicity, we assume that the retailer pays the balance due and starts to sell upon receiving the products. This assumption will not influence the conclusions presented in the paper. Because the selling season of newsvendor-type products is relatively short, we do not consider the interest income from the revenue collected during the selling season. Fig. 1 shows the funding sequence in the supply chain.

Let β be the percentage of the total trading amount that the retailer pays up-front, defined over the continuous interval [0, 1]. The retailer pays βwq as a deposit and the manufacturer starts

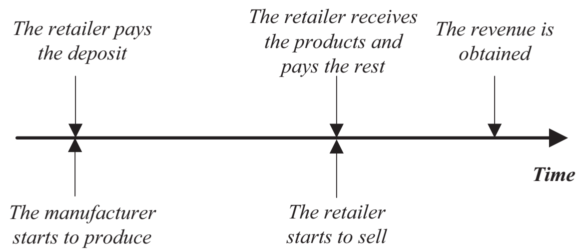

Fig. 1. Funding sequence.

production. The budgets required by the retailer and the manufacturer are $(c_r + w)q$ and $(c_m - \beta w)q$, respectively, when $w \geqslant 0$. In this case, $(c_r + w)q \geqslant 0$. The capital costs in the required budgets depend on w, β, and q. Let $PB_r(w, \beta, q)$ and $PB_m(w, \beta, q)$ be the capital cost functions of the retailer and the manufacturer, respectively. $PB_r(w, \beta, q) \geqslant 0$ when $(w + c_r)q \geqslant 0$, and $PB_m(w, \beta, q) \geqslant 0$ when $(c_m - \beta w)q \geqslant 0$. Additionally, we have $\partial PB_r(w, \beta, q)/\partial w \geqslant 0$ and $\partial PB_m(w, \beta, q)/\partial w \leqslant 0$. When $w \geqslant 0$, we can infer that $\partial PB_r(w, \beta, q)/\partial q \geqslant 0$, $\partial PB_r(w, \beta, q)/\partial \beta \geqslant 0$, and $\partial PB_m(w, \beta, q)/\partial \beta \leqslant 0$. When $c_m \geqslant \beta\, w$, $\partial PB_m(w, \beta, q)/\partial q \geqslant 0$. The total supply chain expected profit is determined by the values of w, β, and q and can be represented as

$$\Pi_{sc}(w, \beta, q) = pE\min(q, D) + sE(q - D)^+ - cq - PB_r(w, \beta, q) - PB_m(w, \beta, q) \tag{1}$$

In a conventional market setting where contracts are not used (Giannoccaro & Pontrandolfo, 2004), w must be greater than 0 to ensure that the manufacturer receives a profit. Under some contracts, however, the manufacturer can still obtain a profit when w is smaller than 0 (Cachon & Lariviere, 2005). In this case, the manufacturer must transfer some funds to the retailer before the final sales revenue is obtained. Because this case is different from the typical open-account financing scheme, we assume that if $w < 0$, then the manufacturer transfers $-wq$ to the retailer when the order is placed. Then, $\beta = 1$ and the budget required by the manufacturer is $(c_m - w)q$. Let $PB_{sc}(w, \beta, q)$ be the capital cost function of the supply chain, where $PB_{sc}(w, \beta, q) = PB_r(w, \beta, q) + PB_m(w, \beta, q)$.

Definition 1 (*Budget thresholds*). The budget threshold of the retailer is the maximum amount of money that the retailer can spend before the final sales revenue is obtained. The budget threshold of the manufacturer is the maximum amount of money that the manufacturer can use before production.

Definition 2 (*Supply chain coordination under budget constraints*). A contract as agreed by supply chain members is said to coordinate the supply chain if the decisions of the members under the contract (i) satisfy budget constraints, and (ii) lead to the maximum profit for the supply chain.

Let TB_r and TB_m be the budget thresholds of the retailer and the manufacturer, respectively. Let DF1 be the supply chain's decision framework that can be described by the following model.

$$\begin{aligned} Max \quad & \Pi_{sc}(w, \beta, q) = pE\min(q, D) + sE(q - D)^+ \\ & \qquad - cq - PB_r(w, \beta, q) - PB_m(w, \beta, q) \\ s.t. \quad & \begin{cases} (c_r + w)q \leqslant TB_r \\ (c_m - \beta w)q \leqslant TB_m \\ (1 - \beta)w \geqslant 0 \\ 0 \leqslant \beta \leqslant 1 \end{cases} \end{aligned} \tag{DF1}$$

The first two constraints guarantee that the required budgets of the members cannot exceed their budget thresholds. The constraints $(1 - \beta)w \geqslant 0$ and $0 \leqslant \beta \leqslant 1$ ensure that $\beta = 1$ when $w < 0$.

Lemma 1. *Under any contract, for any q, the minimum total budget for the supply chain is cq.*

All proofs are located in the Appendix. For a pair $\{TB_r, TB_m\}$, the maximum total budget for the supply chain is $TB_r + TB_m$. From Lemma 1, we can infer that q cannot be greater than $(TB_r + TB_m)/c$. Let q^*_{EB} be the optimal q in DF1 with infinite TB_r and TB_m. Consequently, the optimal q under budget constraints cannot be greater than $\min\{q^*_{EB}, (TB_r + TB_m)/c\}$.

2.2. Revenue-sharing-and-buy-back contracts for supply chain coordination

A composite contract should lead to a higher supply chain profit and to higher flexibility in profit allocation with a low administrative cost. In addition, the composite contract should be easy for managers to understand and use. Based on these requirements, we propose an RSBB contract. Under such contracts, the retailer pays the manufacturer w per unit purchased. Moreover, the manufacturer obtains $(1 - \Phi')$ of the retailer's the total revenues and pays the retailer a buyback rate, b, for per unit unsold at the end of the selling season. Let $\Pi_r(w, \beta, q)$ and $\Pi_m(w, \beta, q)$ be the expected profit functions of the retailer and the manufacturer, respectively. Under the RSBB contract we have

$$\Pi_r(w, \beta, q) = \Phi'\left[pE\min(q, D) + sE(q - D)^+\right] - (w + c_r)q + bE(q - D)^+ - PB_r(w, \beta, q) \tag{2}$$

$$\Pi_m(w, \beta, q) = (1 - \Phi')\left[pE\min(q, D) + sE(q - D)^+\right] - (c_m - w)q - bE(q - D)^+ - PB_m(w, \beta, q) \tag{3}$$

Supply chain coordination is achieved under the RSBB contract when the members' expected profit functions are affine transformations of the expected profit function of the supply chain. Let Φ be a value that determines the profit allocation, defined over the continuous interval [0, 1].

Theorem 1. *For any $\Phi \in [0, 1]$, consider the RSBB contracts with*

$$w + \frac{PB_r(w, \beta, q)}{q} - \frac{\Phi PB_{sc}(w, \beta, q)}{q} = (\Phi' - \Phi)p + \Phi c - c_r \tag{4}$$

$$b = (\Phi' - \Phi)(p - s) \tag{5}$$

Under these contracts, $\Pi_r(w, \beta, q) = \Phi\Pi_{sc}(w, \beta, q)$ and $\Pi_m(w, \beta, q) = (1 - \Phi)\Pi_{sc}(w, \beta, q)$. Both types of members are incentivized to choose the channel-wide optimal w, β, and q that maximize the expected total supply chain profit.

With w, β, q, and a pre-negotiated Φ, the values of Φ' and b can be determined based on Eqs. (4) and (5). Then, the retailer's and the manufacturer's expected profit functions are linear functions of the expected total supply chain profit under the RSBB contract. Under a pre-negotiated Φ, the retailer and the manufacturer obtain their own maximum profits if and only if the supply chain profit is maximized. Therefore, both members will accept the channel-wide optimal w, β, and q, thus achieving supply chain coordination. Under the RSBB contract, members can arbitrarily split the supply chain profit by setting Φ. They can negotiate a value of Φ based on their relative bargaining power (Cachon & Lariviere, 2005).

Managers may cite "*distribution-free*" as a popular criterion for evaluating the feasibility of a contract. See Gallego and Moon (1993) and Wang and Webster (2007) for detailed discussions of the advantages of the distribution-free criterion in the newsvendor problem and supply chain contracts. From Theorem 1, we find that the RSBB contract is distribution-free where $\Pi_r(w, \beta, q) = \Phi\Pi_{sc}(w, \beta, q)$ under D with any distribution. Compared with some other contract types in which the decision variables depend on the distribution of the demand (e.g., Xiong et al., 2011), the distribution-free RSBB contract can be more easily used.

Under the RSBB contract, the supply chain members decide the values of the decision variables at several stages of the process. The timing of the supply chain decision events under the RSBB contract is as follows:

- Before the selling season, the members report TB_r and TB_m and decide the value of Φ. The members decide the values of w, β, and q under DF1.
- The members calculate the values of Φ' and b using Eqs. (4) and (5), based on w, β, q, and Φ.
- The manufacturer receives a deposit of βwq from the retailer, starts production, and delivers all the products to the retailer.
- The retailer pays $(1-\beta)wq$ and sells the products during the selling season.
- At the end of the selling season, the unsold products are salvaged.
- The retailer pays the manufacturer $(1-\Phi')[pE\min(q,D)+sE(q-D)^+]-bE(q-D)^+$.

Under the RSBB contract, the profits of the retailer and the manufacturer depend on Φ. Φ' is used to adjust the components of the profits. As O' is increased, the retailer obtains more revenue from the revenue-sharing mechanism and less revenue from buy-back mechanism. When using the buy-back mechanism, the retailer supplies information about the unsold products to the manufacturer, which saves the cost of monitoring the retailer's revenue.

The RSBB contract requires little additional cost over RS and BB contracts. Under the RS contract, the retailer submits the amount of the sold product to the manufacturer to reveal its total revenue. Other costs may occur due to the money transfers between the retailer and the manufacturer. Under the RSBB contract, the retailer submits the amount of unsold product to the manufacturer, and the manufacturer calculates the buyback credit based on this information. At the end of the selling season, only one money transfer is necessary. The members can sum the revenue shared and the buyback credit to determine the final money transfer. Therefore, the administrative costs of the RS contract and the BB contract also apply to the RSBB contract.

3. Comparison of the revenue-sharing-and-buy-back, revenue-sharing, and buy-back contracts under budget constraints

3.1. Impact of budget constraints on the performance of the contracts

We extend the RS and BB contracts by addressing capital costs and show how budget constraints influence the performance of the RS, BB, and RSBB contracts.

Theorem 2. *For any $\Phi \in [0,\ 1]$, consider the RS contracts with*

$$w+\frac{PB_r(w,\beta,q)}{q}-\frac{\Phi PB_{sc}(w,\beta,q)}{q}=\Phi c-c_r \tag{6}$$

The retailer transfers $(1-\Phi)$ of its total revenue to the manufacturer. Under these RS contracts, $\Pi_r(w,\beta,q)=\Phi\Pi_{sc}(w,\beta,q)$ and $\Pi_m(w,\beta,q)=(1-\Phi)\Pi_{sc}(w,\beta,q)$. Both members are incentivized to choose the channel-wide optimal w, β, and q.

Theorem 3. *For any $\Phi \in [0,\ 1]$, consider the BB contracts with*

$$w+\frac{PB_r(w,\beta,q)}{q}-\frac{\Phi PB_{sc}(w,\beta,q)}{q}=(1-\Phi)p+\Phi c-c_r \tag{7}$$

$$b=(1-\Phi)(p-s) \tag{8}$$

The manufacturer pays the retailer b for per unit unsold. Under these BB contracts, $\Pi_r(w,\beta,q)=\Phi\Pi_{sc}(w,\beta,q)$ and $\Pi_m(w,\beta,q)=(1-\Phi)\Pi_{sc}(w,\beta,q)$. Both members are incentivized to choose the channel-wide optimal w, β, and q.

From Theorems 1 to 3, we can see that the RS and BB contracts are two special cases of our RSBB contract. If we let $\Phi'=\Phi$, then there is no buyback (because $b = 0$) and our RSBB contract will be the same with the RS contract. If we let $\Phi'=1$, then there is no revenue sharing and our RSBB contract will be the same with the BB contract. We can derive that Φ' is a lever that can make the RSBB contract resemble either the RS or the BB contracts. Let w^*, β^*, and q^* be the optimal solutions of DF1. We assume that $\{w^*,\beta^*,q^*\}$ exists, but it needs not to be unique.

Property 1. *For a $\{TB_r, TB_m\}$, the following conditions apply: (i) under the RS and BB contracts and a specific set of $\{w^*, \beta^*, q^*\}$, the profit allocations are fixed; (ii) under a unique set of $\{w^*, \beta^*, q^*\}$, the RS and BB contracts cannot be used to coordinate the supply chain simultaneously unless $w^*+PB_r(w^*,\beta^*,q^*)/q^*-PB_{sc}(w^*,\beta^*,q^*)/q^*=c_m$; and (iii) the RSBB contract can be used to coordinate the supply chain and arbitrarily allocate the profit between the retailer and the manufacturer.*

Under the RS and BB contracts, the value of Φ is fixed for a $\{w, \beta, q\}$. Under a finite number of sets of $\{w^*, \beta^*, q^*\}$, the RS and BB contracts cannot be used to arbitrarily allocate the supply chain profit. Under the RSBB contract, however, Φ depends on w and Φ'. Therefore, although $\{w^*, \beta^*, q^*\}$ is fixed, under the RSBB contract, an arbitrarily determined Φ can be set. Under any $\{TB_r, TB_m\}$, the RSBB contract can be used to achieve the channel-wide optimal q and arbitrarily allocate the supply chain profit.

In practice, managers commonly evaluate capital costs by using the interest rate that has been used in many previous studies on the financial coordination of supply chains (Caldentey & Haugh, 2009; Chen & Cai, 2011). In addition, to achieve supply chain coordination, retailers and manufacturers need to find capital cost functions on which they can agree. Choosing a risk-free interest rate is a quick and administratively cheap approach commonly adopted in previous research (e.g., Lee & Rhee, 2010). Therefore, we assume that supply chain members use the risk-free interest rate, k, to evaluate their capital costs. Let the time between the production and the end of the selling season be t_1 and the time between the arrival of the products and the end of the selling season be t_2, where $t_1 > t_2$. The capital cost function of the retailer can be obtained as $PB_r(w,\beta,q)=\beta wq(I_1-1)+[(1-\beta)w+c_r]q(I_2-1)$ and the capital cost function of the manufacturer is $PB_m(w,\beta,q)=(c_m-\beta w)q(I_1-1)-(1-\beta)wq(I_2-1)$, where $I_j=(1+k)^{tj}, j=1,2$. The capital cost function of the supply chain is $PB_{sc}(w,\beta,q)=PB_{sc}(q)=c_mq(I_1-1)+c_rq(I_2-1)$. Without loss of generality, we assume that $c_mI_1+c_rI_2<p$. Hereafter, we discuss the RS, BB, and RSBB contracts under these capital cost functions.

Property 2. *With any $\{TB_r, TB_m\}$, DF1 can be rewritten as DF2:*

$$\begin{aligned}&Max\quad \Pi_{sc}(w,\beta,q)=\Pi_{sc}(q)=pE\min(q,D)+sE(q-D)^+\\&\qquad\qquad -cq-PB_{sc}(q)\\&\text{s.t.}\quad \begin{cases}(c_r+w)q\leqslant TB_r\\(c_m-w)q\leqslant TB_m\end{cases}\end{aligned} \tag{DF2}$$

Under k, the amount of money paid up front, βw, changes hands between two members in a way that does not influence the supply chain profit. When $\beta=1$, we obtain the widest range of profit allocation, and the supply chain profit remains the same. When the maximum supply chain profit under budget constraints is achieved, the members' profits depend only on a profit allocation that is influenced by w. For any q, w is limited within a range of

$[c_m - TB_m/q, TB_r/q - c_r]$. In addition, we have $PB_r(w, \beta, q) = PB_r(w, q) = wq(I_1 - 1) + c_r q(I_2 - 1)$ and $PB_m(w, \beta, q) = PB_m(w, q) = (c_m - w) q(I_1 - 1)$. Let $F(d)$ be the cumulative probability function of D and let $f(d)$ be the probability density function of D. Denote the inverse function of $F(d)$ as $F^{-1}(\cdot)$. Then, the supply chain's expected profit function can be rewritten as $\Pi_{sc}(q)$.

$$\Pi_{sc}(q) = p\int_0^q xf(x)dx + p\int_q^\infty qf(x)dx + s\int_0^q (q-x)f(x)dx - cq - PB_{sc}(q) \tag{9}$$

We can infer that q^*_{EB} that maximizes $\Pi_{sc}(q)$ should satisfy

$$q^*_{EB} = F^{-1}((p - c_m I_1 - c_r I_2)/(p - s)) \tag{10}$$

When $I_1 = I_2 = 1$, we have $q^*_{EB} = F^{-1}((p-c)/(p-s))$ from Eq. (10), which is the same with the function of the channel-wide optimal q without considering capital costs (e.g., Choi, Li, & Yan, 2008). $\Pi_{sc}(q)$ is increasing in q and $p - c - PB_{sc}(q)/q > 0$ when $q \leqslant q^*_{EB}$. In DF2, the supply chain's total capital cost becomes a function of q, and we can obtain some new and interesting findings. Note that this is a special case of the former decision framework. Consequently, the RSBB contract can be used to coordinate the supply chain and arbitrarily allocate the supply chain profit for any $\{TB_r, TB_m\}$.

Property 3. *Under Φ and q, Φ' and b are increasing in w when w and q satisfy the budget constraints.*

Lemma 2. *When $TB_r + TB_m \leqslant cq^*_{EB}$, there exists a unique optimal $\{w, q\}$ which can be obtained as $\{(TB_r c_m - TB_m c_r)/(TB_r + TB_m), (TB_r + TB_m)/c\}$.*

Let $\{w^*_{BC}, q^*_{BC}\}$ be the unique optimal $\{w, q\}$ shown in Lemma 2. The RS, BB, and RSBB contracts can all be used to coordinate the supply chain and arbitrarily allocate the total profit in the absence of budget constraints. However, different contracts may set different budget thresholds for profit optimization and profit allocation. We divide the budget pairs into three regions:

(I) A pair of budgets is called "sufficient" if under the budget constraints the contract allows members to achieve q^*_{EB} and arbitrarily allocate the profit.
(II) A pair of budgets is called "large" if under the budget constraints the contract allows both types of members to achieve q^*_{EB} and earn profits.
(III) A pair of budgets is called "limited" if under the budget constraints the contract allows both types of members to achieve q^*_{BC} and earn profits.

Other budget pairs are called "inactive" if under the budget constraints the contract does not allow either type of member to earn profits when the channel-wide optimal q is achieved. Letting $G(w) = w + PB_r(w, q)/q$, we can infer that $G'(w) \geqslant 0$ for all $q > 0$. Based on Lemma 2, we infer that the channel-wide optimal q is min $(q^*_{EB}, (TB_r + TB_m)/c)$ in DF2. The channel-wide optimal q is q^*_{EB} when $TB_r + TB_m \geqslant cq^*_{EB}$.

Property 4. *Under the RS and BB contracts, there exist lower bounds on TB_r and TB_m to achieve q^*_{EB} and to allow for arbitrary profit allocation.*

Property 4 defines the budget thresholds for the two members that are necessary to achieve q^*_{EB} and arbitrarily allocate the profit under the RS and the BB contracts (i.e., the thresholds of Regions II_{RS} and II_{BB}). As discussed before, $p - c - PB_{sc}(q)/q > 0$ when $q \leqslant q^*_{EB}$. Considering that $G'(w) \geqslant 0$, we can infer that $G^{-1}(p - c_r) \geqslant G^{-1}(c_m + PB_{sc}(q^*_{EB})/q^*_{EB})$. Therefore, to coordinate the supply chain and arbitrarily allocate the profit, the retailer needs a larger budget under the BB contract than under the RS contract. Additionally, $G^{-1}(c_m + PB_{sc}(q^*_{EB})/q^*_{EB}) > G^{-1}(-c_r)$, and we can infer that the manufacturer needs a smaller budget under the BB contract than under the RS contract. The sums of the budget thresholds under the RS and BB contracts are both larger than cq^*_{EB}. Based on Property 1, the RSBB contract can be used to coordinate the supply chain and arbitrarily allocate the profit if $TB_r + TB_m \geqslant cq^*_{EB}$, which is a looser requirement than is required by the RS and the BB contracts. Therefore, there is no Region II for the RSBB contract.

Property 5. *Under the RS and BB contracts, there exist lower bounds on TB_r and TB_m to allow both types of supply chain members to achieve q^*_{EB} and earn profits.*

Property 5 defines the exact budget thresholds for the two members that are necessary to coordinate the supply chain when $TB_r + TB_m > cq^*_{EB}$ under the RS and the BB contracts (i.e., the thresholds of Regions II_{RS} and II_{BB}). Because the contracts provide profits to the members when the supply chain profit can be arbitrarily allocated, Region I is a sub-region of Region II.

Property 6. *Under the RS and BB contracts, there exist lower bounds on TB_r and TB_m to allow both types of supply chain members to achieve $\{w^*_{BC}, q^*_{BC}\}$ and earn profits.*

Property 6 defines the requirement of TB_r and TB_m in Regions III of RS and BB contracts (i.e., Region III_{RS} and III_{BB}). Based on Property 1, the RSBB contract can be used to coordinate the supply chain for any $\{TB_r, TB_m\}$ for which $TB_r + TB_m \leqslant cq^*_{EB}$. Note that in Region III, the RSBB contract can still be used to arbitrarily allocate the profit.

From Properties 4–6, we see that throughout Regions I–III the retailer needs a larger budget under the BB contract than under the RS contract while the manufacturer needs a smaller budget under the BB contract than under the RS contract. Therefore, the BB contract might be unfair to the retailer.

Property 7. *Under the RS and BB contracts, there exist lower bounds on TB_r and TB_m to allow members to achieve $\{\Phi, q\}$.*

Property 7 defines the exact budget thresholds for the two members to achieve a pair of Φ and q under RS and the BB contracts. To obtain the same profit, the retailer needs a larger budget under the BB contract than under the RS contract. The RS and BB contracts cannot allow for supply chain coordination if the members fail to obtain the necessary budgets. When one member is budget constrained and the other member has a sufficient budget, supply chain coordination may not be achieved under either the RS or BB contracts. However, the RSBB contract can always be used to achieve the optimal q of DF2 and arbitrarily allocate the supply chain profit.

3.2. Impact of capital costs on the performance of the contracts

We develop Property 8 which shows the thresholds of Regions III_{RS} and III_{BB}.

Property 8. *Region III_{RS} is the area defined by $TB_m c_r(I_1 - I_2) = TB_r(c_m I_1 + c_r I_2)$, $TB_m = 0$, and $TB_r + TB_m = cq^*_{EB}$. Region III_{BB} is the area defined by $TB_m = TB_r(c_m I_1 + c_r I_2 - p)/[c_r(I_1 - I_2) + p]$, $TB_m = 0$, and $TB_r + TB_m = cq^*_{EB}$.*

As discussed before, when $PB_r(w, \beta, q) = PB_r(w, q) = wq(I_1 - 1) + c_r q(I_2 - 1)$, we can show that $G(w) = wI_1 + c_r(I_2 - 1)$ and $G^{-1}(y) = [y - c_r(I_2 - 1)]/I_1$, where $G'(w) > 0$. In this case, we obtain $w = [(\Phi' - \Phi)p + \Phi(c_m I_1 + c_r I_2) - c_r I_2]/I_1$ under the RSBB contract. Using the theorems discussed above, the first two budget regions can be obtained for the three contracts. Region III can be obtained from Property 8.

(I) Sufficient budget pairs. From Property 4, under the RS contract, $TB_r \geqslant cq^*_{EB}$ and $TB_m \geqslant (c_m I_1 + c_r I_2)q^*_{EB}/I_1$; under the BB contract, $TB_r \geqslant [p + c_r(I_1 - I_2)]q^*_{EB}/I_1$ and $TB_m \geqslant 0$. From Property 2, under the RSBB contract, $TB_r + TB_m \geqslant cq^*_{EB}$.

(II) Large budget pairs. From Property 5, under the RS contract, $TB_r \geqslant c_r(I_1 - I_2)q^*_{EB}/I_1, TB_m \geqslant 0$, and $TB_r + TB_m \geqslant cq^*_{EB}$; under the BB contract, $TB_m \geqslant (c_m I_1 + c_r I_2 - p)q^*_{EB}/I_1, TB_r \geqslant cq^*_{EB}$, and $TB_r + TB_m \geqslant cq^*_{EB}$.

(III) Limited budget pairs. From Property 8, under the RS contract, $TB_m \geqslant 0$, $TB_m c_r(I_1 - I_2) \leqslant TB_r(c_m I_1 + c_r I_2)$, and $TB_r + TB_m \leqslant cq^*_{EB}$; under the BB contract, $TB_m \leqslant 0$, $TB_m \geqslant TB_r(c_m I_1 + c_r I_2 - p)/(c_r(I_1 - I_2) + p)$, and $TB_r + TB_m \leqslant cq^*_{EB}$.

In Regions I and II, the ranges of TB_r and TB_m are independent of each other because q^*_{EB} is not determined by budget thresholds. In Region III, however, q^*_{BC} depends on budget thresholds. Therefore, Region III appears different from the other two regions. When $I_1 - I_2$ is relatively small, one can assume that $I = I_1 = I_2$. From Property 8, when $I = I_1 = I_2$, one sees that Region III of the RS contract is the area defined by $TB_m = 0$, $TB_r = 0$, and $TB_r + TB_m = cq^*_{EB}$. Region III of the BB contract is the area defined by $TB_m = 0$, $TB_m = TB_r(cI/p - 1)$ and $TB_r + TB_m = cq^*_{EB}$. Under the BB contract, q^*_{BC} can be achieved when $TB_r \geqslant cq^*_{BC}$, $TB_m \geqslant (c\ -p/I)q^*_{BC}$, and $TB_r + TB_m = cq^*_{BC}$. Table 1 summarizes the budget regions for the case of $I = I_1 = I_2$.

Tables 1(a) and 1(b) show that the retailer needs a larger budget under the BB contract than under the RS contract to achieve the same performance, but the manufacturer needs a smaller budget to prosper with a BB contract. The symbol "NA" means that there is no constraint. Under the RSBB contract, the only requirement for the budgets is the constraint noted in Lemma 1, which is less strict than the requirements under RS and BB contracts. We summarize the conclusions in Fig. 2, in which I_{RS}&I_{BB} (II_{RS}&II_{BB}) represents the overlap between I_{RS} and I_{BB} (II_{RS} and II_{BB}).

As can be seen in Fig. 2, regions for the RS and BB contracts have different boundaries. The smallest TB_r in Regions I_{RS} and II_{RS} are smaller than those in Regions I_{BB} and II_{BB}, respectively; the smallest TB_m in Regions I_{RS} and II_{RS} are greater than those in Regions I_{BB} and II_{BB}, respectively. Moreover, there exist Regions I_{RS}&I_{BB} and II_{RS}&II_{BB}. Note that the channel-wide optimal $\{w, q\}$ is $\{w^*_{BC}, q^*_{BC}\}$ for $\{TB_r, TB_m\}$ when $TB_r + TB_m < cq^*_{EB}$ (see Lemma 2). With the proof of Property 8, we can show that TB_m should be no greater than 0 to achieve w^*_{BC} under the BB contract, and TB_m should be no smaller than 0 to achieve w^*_{BC} under the RS contract. Hence, there is no overlap between Regions III_{RS} and III_{BB} except the line between (0, 0) and (cq^*_{EB},0). The expected profit function of the manufacturer under the BB contract can be obtained as $\Pi_m(\Phi, b, w, q) = (w - c_m)q - bE(q - D)^+ - PB_m(w, q)$ in which $b \geqslant 0$ and $PB_m(w, q)$

Table 1
Examples of budget regions under the RS, BB, and RSBB contracts.

	I			II		
	RS	BB	RSBB	RS	BB	RSBB
(a)						
TB_r	$\geqslant cq^*_{EB}$	$\geqslant pq^*{}_{EB}/I$	NA	$\geqslant 0$	$\geqslant cq^*_{EB}$	NA
TB_m	$\geqslant cq^*_{EB}$	$\geqslant 0$	NA	$\geqslant 0$	$\geqslant (c - p/I)q^*_{EB}$	NA
$TB_r + TB_m$	$\geqslant cq^*_{EB}$	$\geqslant cq^*_{EB}$	$\geqslant cq^*_{EB}$	$\geqslant cq^*_{EB}$	$\geqslant cq^*_{EB}$	$\geqslant cq^*_{EB}$
	III					
	RS	BB			RSBB	
(b)						
TB_r	$\geqslant 0$	$\geqslant cq^*_{BC}$			NA	
TB_m	$\geqslant 0$	$\geqslant (c - p/I)q^*_{BC}$			NA	
$TB_r + TB_m$	$=cq^*_{BC}$	$=cq^*_{BC}$			$=cq^*_{BC}$	

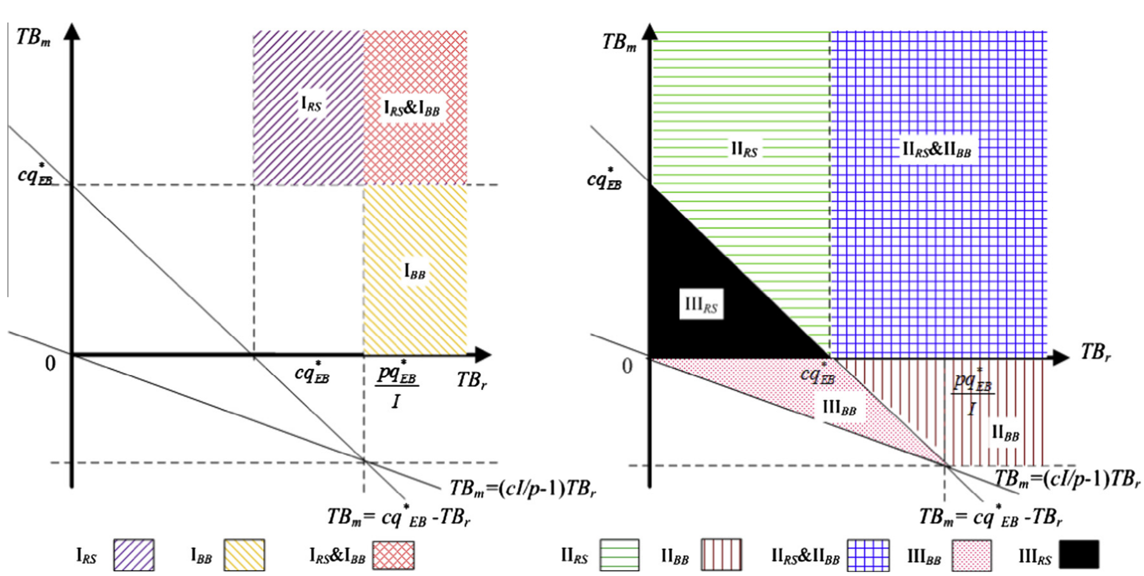

Fig. 2. Comparison of budgets under the RS and BB contracts.

$= (c_m - w)q(I_1 - 1)$. Because the manufacturer's revenues are generated from wq under the BB contract, $(c_m - wq)$ should be no greater than 0 to guarantee a profit for the manufacturer. Therefore, TB_m can be smaller than zero, and Regions II_{BB} and III_{BB} cover some areas in which $TB_m < 0$.

3.3. Optimal decisions under the revenue-sharing and buy-back contracts

Based on Inequalities (A.13) and (A.14), and $0 \leqslant \Phi \leqslant 1$, for $\{TB_r, TB_m\}$ as well as the corresponding channel-wide optimal q, we can find a lower and upper bounds on Φ that are influenced by the budget constraints under the RS and the BB contracts. We denote these lower and upper bounds as Φ^*_{min} and Φ^*_{max} with $0 \leqslant \Phi^*_{min} \leqslant \Phi^*_{max} \leqslant 1$, respectively. We can find budget pairs under which there is no feasible Φ^*_{min} and Φ^*_{max} under the RS or BB contract. We can see that Φ^*_{min} and Φ^*_{max} affect the upper bounds on the manufacturer's and the retailer's expected profits, respectively. Under the RS contract and the channel-wide optimal q, the retailer can increase Φ^*_{max} by increasing TB_r while the manufacturer can decrease Φ^*_{min} by increasing TB_m. However, under the BB contract and the channel-wide optimal q, increasing TB_r may only decrease Φ^*_{min} and increasing TB_m may only increase Φ^*_{max}. This result means that, for each member, the budget threshold and the lower bound on the expected profit are negatively correlated under the BB contract. Consequently, the BB contract can be unfair to both retailer and manufacturer, and the members could benefit by pretending to be subject to greater budget constraints than they actually face. This phenomenon could be more significant when p is increased. Therefore, we conjecture that the members may have a greater incentive to increase their budgets under the RS contract than under the BB contract.

Because of cases in which RS and BB contracts cannot be used to arbitrarily allocate the supply chain profit (i.e., $\Phi^*_{min} > 0$ or $\Phi^*_{max} < 1$), supply chain members may prefer a local optimal decision to the channel-wide optimal one. Moon et al. (2015) showed real-world examples in which powerful members may have budget constraints but can determine Φ and q to maximize their own profits. We discuss the retailer's optimal decisions under the RS and BB contracts; the discussion of those of the manufacturer is similar. To understand retailer's decisions with RS and BB contracts, let $\Phi_U (0 \leqslant \Phi_U \leqslant 1)$ be the largest Φ that the retailer can request based on its bargaining power. Denote the retailer's optimal Φ and q as Φ^*_r and q^*_r, respectively. Considering Inequality (A.13) and $PB_r(w, q) = wq(I_1 - 1) + c_r q(I_2 - 1)$, we can obtain the retailer's decision framework under the RS contract as DF3:

$$\begin{aligned} &Max \quad \Pi_r(w,q) = \Pi_r(\Phi,q) = \Phi \Pi_{sc}(q) \\ &s.t. \quad \begin{cases} [\Phi(c_r I_2 + c_m I_1) - c_r(I_2 - I_1)]q \leqslant TB_r I_1 \\ [c_r I_2 + c_m I_1 - \Phi(c_r I_2 + c_m I_1)]q \leqslant TB_m I_1 \\ 0 \leqslant \Phi \leqslant \Phi_U \end{cases} \end{aligned} \tag{DF3}$$

Φ^*_{min} and Φ^*_{max} under the RS contract can be obtained from the first two constraints in DF3 with $\Phi^*_{min} \geqslant 0$ and $\Phi^*_{max} \leqslant 1$. When Φ_U is within the range of $[\Phi^*_{min}, \Phi^*_{max}]$, it is easy to prove that q^*_r is the same with the channel-wide optimal q and $\Phi^*_r = \Phi_U$. If Φ_U is greater than Φ^*_{max}, then the retailer might benefit from requesting Φ greater than Φ^*_{max} and ordering q smaller than the channel-wide optimal q, which still satisfies the budget constraints. In this case, Φ^*_r and q^*_r of DF3 cannot achieve supply chain coordination. Therefore, the RS contract may fail to allow for supply chain coordination if the retailer has sufficient bargaining power to decide Φ and q. With the same approach, we obtain the retailer's decision framework under the BB contract as DF4:

$$\begin{aligned} &Max \quad \Pi_r(w,q) = \Pi_r(\Phi,q) = \Phi \Pi_{sc}(q) \\ &s.t. \quad \begin{cases} [\Phi(c_r I_2 + c_m I_1) - c_r(I_2 - I_1) + (1-\Phi)p]q \leqslant TB_r I_1 \\ (1-\Phi)(c_r I_2 + c_m I_1 - p)q \leqslant TB_m I_1 \\ 0 \leqslant \Phi \leqslant \Phi_U \end{cases} \end{aligned} \tag{DF4}$$

Φ^*_{min} and Φ^*_{max} under the BB contract can be obtained from the first two constraints in DF4 with $\Phi^*_{min} \geqslant 0$ and $\Phi^*_{max} \leqslant 1$. It can be shown that, when $\{TB_r, TB_m\}$ is located in Region III_{BB}, $\Phi^*_r = \Phi^*_{min} = \Phi^*_{max}$ and $q^*_r = q^*_{BC}$ in DF4. Note that $(c_r I_2 + c_m I_1) < p$. When Φ_U is greater than Φ^*_{max} and $\{TB_r, TB_m\}$ is located in Region II_{BB} with $TB_m < 0$, the retailer might benefit from requesting Φ greater than Φ^*_{max} and ordering q greater than the channel-wide optimal q, which still satisfies the budget constraints. In this case, Φ^*_r and q^*_r cannot achieve supply chain coordination. Therefore, the BB contract may not allow for supply chain coordination if the retailer has sufficient power to decide Φ and q.

3.4. Information asymmetry: When budget threshold information is private

In the previous sections, we followed the assumption that the budget thresholds of the retailer and the manufacturer are publicly known to each other. In some cases, however, this information is private, leading to the following question: Will supply chain members pretend to be more budget constrained to gain an advantage? If they do, can the RSBB contract be used to prevent such cheating?

Let B_r and B_m be the budgets of the retailer and the manufacturer, with $B_r = (c_r + w)q$ and $B_m = (c_m - w)q$. The agreed-upon capital costs, $PB_r(B_r)$ and $PB_m(B_m)$, have been considered in $\Pi_{sc}(q)$. Under the RSBB contract, $PB_r(B_r)$ and $PB_m(B_m)$ are shared between the retailer and the manufacturer. If $PB_r(B_r)$ and $PB_m(B_m)$ can represent all related capital costs, the supply chain members do not have the incentive to pretend to be more budget constrained under the RSBB contract. In the real world, however, some capital costs, such as those related to capital management, are difficult to quantify and cannot be included in $PB_r(B_r)$ and $PB_m(B_m)$. In this study, we refer to these costs as the *capital management cost*. Let $O_r(B_r)$ and $O_m(B_m)$ be the capital management cost functions of the retailer and the manufacturer as increasing with B_r and B_m, respectively. Note that $O_r(B_r)$ and $O_m(B_m)$ should have small values compared with $\Pi_{sc}(q)$ because the main part of the capital cost, $PB_r(B_r)$ and $PB_m(B_m)$, has been considered in $\Pi_{sc}(q)$. For simplicity, we assume that the channel-wide optimal q still follow Eq. (10) and Lemma 2. Let TB^o_r and TB^o_m be the real budget thresholds of the retailer and manufacturer, respectively. Let B^o_r and B^o_m be the budgets of the retailer and the manufacturer under TB^o_r and TB^o_m. Without loss of generality, we discuss the case wherein the retailer reveals a budget threshold, TB^d_r, and the manufacturer reacts. Let $\Pi_{sc}(q^* \mid TB_r + TB_m)$ be the channel-wide maximized profit under TB_r and TB_m.

Property 9. *For $\Phi \in [0, 1]$, the retailer can gain an advantage by revealing $TB^d_r (< TB^o_r)$.*

To avoid cheating under the RSBB contract, we propose the profit allocation adjustment (PAA) approach, which links profit allocation with the budgets of supply chain members. Under the PAA paradigm, an original profit allocation is determined and adjusted by consideration of the members' budgets. This approach has been widely used in many supply chains in which members cooperate and share the supply chain profit, such as the truck brake supply chain in China. Let Φ be a function of B_r and B_m, with $\Phi(B_r, B_m) \in [0, 1]$. The expected profit functions of the retailer and manufacturer are $\Phi\ (B_r, B_m)\ \Pi_{sc}(q)$ and $(1 - \Phi(B_r, B_m))\ \Pi_{sc}(q)$, respectively. Let $B_{sc} = B_r + B_m$. Under the PAA approach, we use $\Phi_F \in [0,\ 1]$ and set $L \in [0,\ 1]$ to create the target percentage of B_r in B_{sc} to determine the original profit allocation:

$$\Phi(B_r, B_m) = \Phi_F - \lambda(L - B_r/B_{sc}).$$

Lemma 3. *In the RSBB contracts used under the PAA approach, the retailer and the manufacturer will not be intend to pretend to be more budget constrained simultaneously.*

Property 10. *In the RSBB contracts used under the PAA approach, the retailer's expected profit is decreased if it pretends to be more budget constrained.*

Φ_F and L are used to determine an original profit allocation that is independent of TB_r and TB_m. This original profit allocation is adjusted by considering the budgets that depend on revealed budget thresholds. Under a large λ, if one member reveals a relatively small budget threshold and requires a small budget, the other member will keep its real budget threshold to obtain a higher profit. In this case, the member who cheats will earn a smaller profit than if it did not cheat. Consequently, supply chain members cannot gain an advantage by cheating under the RSBB contract with the PAA approach. As a result, this profit allocation policy is used in some truck brake supply chains in China. The retailer and manufacturer cooperate for a larger total profit and the budgets of supply chain members are considered when they split the total profit.

4. Numerical experiments

Assume that D follows a normal distribution with a mean of 1000 units and a standard deviation of 300; p is \$10; s is \$1; c_r and c_m are \$1/unit and \$4/unit, respectively. The cycle time t_1 is 4 months, and t_2 is 2 months. The risk-free interest rate, k, is 0.55% per month. To focus on the impact of the interest rate while considering $c_r(I_1 - I_2)$ to be relatively small, we assume that $I = I_1 = I_2 = (1+k)^{t1}$.

4.1. The revenue-sharing-and-buy-back contract under budget constraints

Consider that RSBB contract is used for supply chain coordination.

First, suppose that the retailer and the manufacturer reveal the values of TB_r and TB_m which are \$4000 and \$2000, respectively. Because the RSBB contract can always arbitrarily allocate the supply chain profit, we suppose that the members decide $\Phi = 0.6$.

Second, based on Eq. (10), we obtain that $q^*_{EB} = 1032$ by using MATLAB and cq^*_{EB} is \$5160. Because the total budget of the supply chain (i.e., \$6000) is greater than cq^*_{EB}, we obtain that the RSBB contract can achieve q^*_{EB}. From the constraints in DF2, we see that w can vary over a range of $[c_m - TB_m/q^*_{EB},\ TB_r/q^*_{EB} - c_r]$ (i.e., [2.06, 2.87]) to achieve q^*_{EB}. Suppose that the members agree to make $w = 2.36$.

Third, we have Φ' is 0.6368 from Eq. (4) in which $\beta = 1$. Subsequently, we can determine b by using Eq. (5).

The retailer pays the manufacturer wq^*_{EB} in prior to the selling season and $(1-\Phi')$ of its total revenue (sales revenue and salvage revenue) at the end of the selling season. The sales revenue and the salvage revenue are \$8956.37 and \$136.36, as calculated by $p\left(\int_0^{1032} xf(x)dx + \int_{1032}^{\infty} 1032f(x)dx\right)$ and $s\int_0^{1032}(1032-x)f(x)dx$, respectively. At these values, the retailer's expected profit will be 60% of $\Pi_{sc}(q)$. From Eq. (9), we can obtain $\Pi_{sc}(q^*_{EB}) = \$3818.27$. Table 2 shows the optimal RSBB contract setting to coordinate the supply chain under different values of k when $\Phi = 0.6$.

Table 2
The decision variables under the RSBB contract.

k (%)	w (\$ per unit)	Φ'	b (\$ per unit)	Π_r(\$)	Π_{sc}(\$)
0.85	2.05	0.605	0.046	2253.10	3755.17
	2.35	0.636	0.325	2253.10	3755.17
	2.65	0.667	0.605	2253.10	3755.17
	2.89	0.692	0.828	2253.10	3755.17
0.55	2.06	0.606	0.055	2290.96	3818.27
	2.36	0.637	0.331	2290.96	3818.27
	2.66	0.667	0.607	2290.96	3818.27
	2.87	0.689	0.800	2290.96	3818.27
0.25	2.07	0.607	0.063	2328.68	3881.13
	2.37	0.637	0.336	2328.68	3881.13
	2.67	0.668	0.609	2328.68	3881.13
	2.85	0.686	0.772	2328.68	3881.13

As Property 3 states, both Φ' and b increase with w. Suppose that k is decreased to 0.10% per month, t_1 is decreased to 3 months, and TB_r and TB_m are decreased to \$3500 and \$1700, respectively. Then, based on Eq. (10) we have $q^*_{EB} = 1041$. The total budget to achieve q^*_{EB} is \$5205, which is larger than the sum of the decreased TB_r and TB_m (i.e., \$5200). In this case, w is fixed (i.e., $(TB_rc_m - TB_mc_r)/(TB_r + TB_m) = 2.365$) (see Lemma 2) and the supply chain can maximize the total profit with $q^*_{BC} = (TB_r + TB_m)/c = 1040$. By putting the related values into Table 1(b), we find that the budget pair is located in Region III_{RSBB}, which means that through the RSBB contract q^*_{BC} can be achieved and the total profit can be arbitrarily allocated. By the same approach, we found that the supply chain's expected profit is \$3917.68. Table 3 shows the optimal solution under the RSBB contract used to coordinate the supply chain as Φ varies from 0.4 to 0.7.

Table 3 shows that the retailer's expected profit and Φ' increase with Φ. The buyback rate, b, decreases as Φ is increased. It is easy to show that the expected profit of the retailer only depends on Φ.

4.2. The revenue-sharing and buy-back contracts under budget constraints

Suppose that k is 0.55% per month and t_1 is 4 months. Let q^*_{sc} be the channel-wide optimal q for $\{TB_r, TB_m\}$. From the first two constraints in DF3, we discern that under the RS contract, $\Phi cq \leqslant TB_r$ and $(1-\Phi)cq \leqslant TB_m$ when $I = I_1 = I_2$. Considering $0 \leqslant \Phi \leqslant 1$, we obtain $\Phi^*_{min} = max\{0, 1 - TB_m/(cq^*_{sc})\}$ and $\Phi^*_{max} = min\{1, TB_r/(cq^*_{sc})\}$ under the RS contract. From the first two constraints in DF4, we discern that under the BB contract, $\Phi\ cIq + (1-\Phi)pq \leqslant TB_rI$ and $(1-\Phi)(cI - p)q \leqslant TB_mI$ when $I = I_1 = I_2$. Considering $0 \leqslant \Phi \leqslant 1$, we have $\Phi^*_{min} = max\{0, (p - TB_rI/q^*_{sc})/(p\text{-}cI)\}$ and $\Phi^*_{max} = min\{1, (p - cI + TB_mI/q^*_{sc})/(p - cI)\}$ under the BB contract. Note that, for the *inactive* budge pairs under the RS or BB contract, there is no feasible $[\Phi^*_{min}, \Phi^*_{max}]$ that satisfies $0 \leqslant \Phi^*_{min} \leqslant \Phi^*_{max} \leqslant 1$. In these cases, neither the RS nor the BB contract can achieve q^*_{sc} and bring profits to the retailer and the manufacturer.

Under the RSBB contract, which can be used to achieve supply chain coordination and arbitrarily allocate the supply chain profit

Table 3
The decision variables under the RSBB contract for different profit allocations.

Φ	Φ'	b (\$ per unit)	Π_r(\$)	Π_{sc}(\$)
0.400	0.537	1.232	1567.07	3917.68
0.500	0.587	0.781	1958.84	3917.68
0.600	0.637	0.330	2350.61	3917.68
0.700	0.686	−0.122	2742.38	3917.68

Table 4
Flexibility in profit allocation under the RS and BB contracts.

TB_r	TB_m	q^*	RS				BB			
			Φ^*_{min}	Φ^*_{max}	Gap (%)	Region	Φ^*_{min}	Φ^*_{max}	Gap (%)	Region
10,096	5160	1032	0.000	1.000	0.0	I_{RS}	0.000	1.000	0.0	I_{BB}
10,096	5000	1032	0.031	1.000	3.1	II_{RS}	0.000	1.000	0.0	I_{BB}
10,096	3000	1032	0.419	1.000	41.9	II_{RS}	0.000	1.000	0.0	I_{BB}
10,000	5160	1032	0.000	1.000	0.0	II_{RS}	0.020	1.000	2.0	II_{BB}
8000	5160	1032	0.000	1.000	0.0	II_{RS}	0.425	1.000	42.5	II_{BB}
8000	5000	1032	0.031	1.000	3.1	II_{RS}	0.425	1.000	42.5	II_{BB}
6000	5000	1032	0.031	1.000	3.1	II_{RS}	0.830	1.000	83	II_{BB}
5160	5000	1032	0.031	1.000	3.1	II_{RS}	1.000	1.000	100	II_{BB}
4000	5000	1032	0.031	0.775	25.6	II_{RS}	NF	NF	NF	NF
2000	5000	1032	0.031	0.387	64.4	II_{RS}	NF	NF	NF	NF
8000	3000	1032	0.419	1.000	41.9	II_{RS}	0.425	1.000	42.5	II_{BB}
8000	1000	1032	0.807	1.000	80.7	II_{RS}	0.425	1.000	42.5	II_{BB}
8000	0	1032	1.000	1.000	100.0	II_{RS}	0.425	1.000	42.5	II_{BB}
8000	−1000	1032	NF	NF	NF	NF	0.425	0.797	62.8	II_{BB}
8000	−2000	1032	NF	NF	NF	NF	0.425	0.594	83.1	II_{BB}
3000	2000	1000	0.600	0.600	100.0	III_{RS}	NF	NF	NF	NF
3000	1000	800	0.750	0.750	100.0	III_{RS}	NF	NF	NF	NF
4000	−1000	600	NF	NF	NF	NF	0.651	0.651	100.0	III_{BB}
3000	−1000	400	NF	NF	NF	NF	0.477	0.477	100.0	III_{BB}

NF: there is no feasible value.

under any $\{TB_r, TB_m\}$, we obtain $\Phi^*_{max} - \Phi^*_{min} = 1$. Then, we evaluate the flexibility in profit allocation under the RS and BB contracts by using Gap = $[1 - (\Phi^*_{max} - \Phi^*_{min})/1] \times 100\%$ with $0 \leqslant \text{Gap} \leqslant 100\%$. A larger Gap shows that the target contract has a lower flexibility for profit allocation. Table 4 shows the flexibility for profit allocation under the RS and BB contracts with different $\{TB_r, TB_m\}$.

As Table 1(a) shows, when $TB_r \geqslant pq^*_{EB}/I$ and $TB_m \geqslant cq^*_{EB}$, $\{TB_r, TB_m\}$ is located in the overlap of Regions II_{RS} and I_{BB}. Because $q^*_{EB} = 1032$, we obtain pq^*_{EB}/I = 10,096 and $cq^*_{EB} = 5160$. From Table 4, we can see that when $TB_r = \$10,096$ and $TB_m = \$5160$, both the RS and BB contracts can achieve supply chain coordination and can be used to arbitrarily allocate supply chain profit.

When $TB_r \geqslant \$10,096$ and $0 \leqslant TB_m \leqslant \$5160$, $\{TB_r, TB_m\}$ is located in the overlap of Regions II_{RS} and I_{BB}. Then, the gap of the RS contract is decreasing with TB_m. When $\$5160 \leqslant TB_r \leqslant \$10,096$ and $TB_m \geqslant \$5160$, $\{TB_r, TB_m\}$ is located in the overlap of Regions I_{RS} and II_{BB}. Then, the gap of the BB contract is decreasing with TB_r.

As Table 4 shows, when $\{TB_r, TB_m\}$ is located in Regions II_{RS} and $TB_r < \$5160$, there is no feasible profit allocation for q^*_{EB} under the BB contract and the gap of the RS contract is decreasing with TB_r. When $\{TB_r, TB_m\}$ is located in Regions II_{BB} and $TB_m < 0$, there is no feasible profit allocation for q^*_{EB} under the RS contract and the gap of the BB contract is decreasing with TB_m. When $\{TB_r, TB_m\}$ is located in the overlap of Regions II_{RS} and II_{BB}, the gap of the RS contract is decreasing with TB_m and the gap of the BB contract is decreasing with TB_r.

When $TB_r + TB_m < \$5160$, the RS contract cannot achieve supply chain coordination if $TB_m < 0$, while the BB contract cannot achieve supply chain coordination if $TB_m > 0$. Moreover, the profit allocation is fixed (i.e., Gap = 100%) under these two contracts.

By solving DF3 and DF4 with MATLAB, we obtained the retailer's optimal decisions under the RS and BB contracts, as Tables 5 and 6 illustrate. Because Φ^*_{max} is not influenced by TB_m under the RS contract, we tested different values of TB_r and kept $TB_m = \$2500$ in Table 5. For example, when $TB_r = \$4000$ and $TB_m = \$2500$ are considered and the values of p, c, I, and q^*_{EB} are placed into Table 1(a), we see that the budget pair is located in Region I_{RS}. Therefore, the RS contract can achieve q^*_{EB} and bring profits to the retailer and the manufacturer that cannot be achieved under the BB contract. Because $\Phi^*_{min} = max\{0, 1 - TB_m/(cq^*_{sc})\}$ and $\Phi^*_{max} = min\{1, TB_r/(cq^*_{sc})\}$ under the RS contract, we discern that Φ is limited in the range of [0.516, 0.775] when $q^*_{sc} = q^*_{EB}$. The RS contract cannot be used to coordinate the supply chain if Φ^*_r is outside this range. When it orders q^*_{EB}, the retailer's maximal expected profit is $0.775 \times \Pi_{sc}(q^*_{EB})$, which is equal to \$2959.16. In this case, $\Phi^*_{max} cq^*_{EB} = 3999$. A retailer who requests Φ greater than Φ^*_{max} should order q smaller than q^*_{EB} to satisfy budget constraints. As

Table 5
The retailer's optimal decision under the RS contract.

		Φ_U	Φ^*_r	q^*_r	$\Pi_r(q^*_r)$	$\Pi_{sc}(q^*_r)$	$\Pi_{sc}(q^*_{EB})$
$\{TB_r, TB_m\}$=	{4000, 2500}	0.85	0.850	941	3203.00	3768.23	3818.27
$[\Phi^*_{min}, \Phi^*_{max}]$=	[0.516, 0.775]	0.75	0.750	1032	2863.70	3818.27	3818.27
		0.65	0.650	1032	2481.88	3818.27	3818.27
		0.55	0.550	1032	2100.05	3818.27	3818.27
$\{TB_r, TB_m\}$=	{3500, 2500}	0.85	0.850	823	3026.72	3560.85	3818.27
$[\Phi^*_{min}, \Phi^*_{max}]$=	[0.516, 0.678]	0.75	0.750	933	2819.34	3759.12	3818.27
		0.65	0.650	1032	2481.88	3818.27	3818.27
		0.55	0.550	1032	2100.05	3818.27	3818.27
$\{TB_r, TB_m\}$=	{3000, 2500}	0.85	0.85	705	2732.44	3214.63	3818.27
$[\Phi^*_{min}, \Phi^*_{max}]$=	[0.516, 0.581]	0.75	0.75	800	2627.44	3503.25	3818.27
		0.65	0.65	923	2435.36	3746.70	3818.27
		0.55	0.55	1032	2100.05	3818.27	3818.27

Table 6
The retailer's optimal decision under the BB contract.

		Φ_U	Φ_r^*	q_r^*	$\Pi_r(q_r^*)$	$\Pi_{sc}(q_r^*)$	$\Pi_{sc}(q_{EB}^*)$
		0.85	0.810	1102	3069.88	3789.97	3818.27
$\{TB_r, TB_m\}$=	{8000, −1000}	0.75	0.750	1032	2863.70	3818.27	3818.27
$[\Phi_{min}^*, \Phi_{max}^*]$=	[0.425, 0.797]	0.65	0.650	1032	2481.88	3818.27	3818.27
		0.55	0.550	1032	2100.05	3818.27	3818.27
		0.85	0.725	1141	2718.74	3749.98	3818.27
$\{TB_r, TB_m\}$=	{8000, −1500}	0.75	0.725	1141	2718.74	3749.98	3818.27
$[\Phi_{min}^*, \Phi_{max}^*]$=	[0.425, 0.696]	0.65	0.650	1032	2481.88	3818.27	3818.27
		0.55	0.550	1032	2100.05	3818.27	3818.27
		0.85	0.647	1185	2384.43	3685.37	3818.27
$\{TB_r, TB_m\}$=	{8000, −2000}	0.75	0.647	1185	2384.43	3685.37	3818.27
$[\Phi_{min}^*, \Phi_{max}^*]$=	[0.425, 0.594]	0.65	0.647	1185	2384.43	3685.37	3818.27
		0.55	0.550	1032	2100.05	3818.27	3818.27

Table 5 shows, the retailer can expect a profit higher than $2959.16 by setting $\Phi = \Phi_r^* = 0.850$ and $q = q_r^* = 941$, which satisfy budget constraints. However, in this circumstance the supply chain coordination cannot be achieved under the RS contract, and the RSBB contract can achieve a higher expected profit for the supply chain than can the RS contract. This improvement can be considerable when TB_r is decreasing.

When $TB_r = \$8000$ and $TB_m = -\$1000$, the budget pair is located in Region II_{BB}. Because $\Phi_{min}^* = max\{0, (p - TB_r I/q_{sc}^*)/(p - cI)\}$ and $\Phi_{max}^* = min\{1, (p - cI + TB_m I/q_{sc}^*)/(p\text{-}cI)\}$ under the BB contract, we find that Φ is limited in the range of [0.425, 0.797] to achieve q_{EB}^*. The retailer's maximal expected profit is $0.797 \times \Pi_{sc}(q_{EB}^*)$, which is equal to $3043.16. In this case, $(1 - \Phi_{max}^*)(cI - p)q_{EB}^* = -1024$ and $TB_m I = -1022$. A retailer who requests Φ greater than Φ_{max}^* should order q greater than q_{EB}^* to satisfy the budget constraints because $cI < p$. As Table 6 shows, the retailer can expect a profit higher than $3043.16 by setting $\Phi = \Phi_r^* = 0.810$ and $q = q_r^* = 1102$, which satisfy budget constraints.

Based on the above discussion, we can see that if the retailer has high bargaining power to determine Φ and q, supply chain coordination might not be achieved under the RS and the BB contracts. However, because the RSBB contract can be used to achieve supply chain coordination and arbitrarily divide the supply chain profit, one can always find a profit allocation scenario under which supply chain members are incentivized to select the channel-wide optimal q. Therefore, our RSBB contract can achieve higher profits to supply chain members than the RS and BB contracts. This improvement in profits can be more significant when Φ_U is high.

5. Managerial implications and conclusions

In this paper, we analyzed the coordination of a supply chain consisting of a retailer and a manufacturer under budget constraints. We identified the limitations of the RS and the BB contracts in this type of supply chain. We proposed an RSBB contract that uses both revenue-sharing and buy-back mechanisms. The RSBB contract can be used to coordinate the supply chain and arbitrarily allocate the total profit under budget constraints. The additional administrative cost of the RSBB contract is small compared to those of the RS and the BB contracts, so the economic efficiency of the RSBB contract is high.

Our RSBB contract differs from the contracts studied by past researchers in two ways. First, our RSBB is distribution-free. In practice, it is not easy to obtain the exact distribution of demand such that a distribution-free contract may be preferable because the profit allocation is independent of the real demand. Second, our RSBB contract may prevent members from pretending to be more budget constrained than they are in reality.

For a supply chain in which the capital costs are considered, we divide the budget scenarios into three regions in which the RS, BB, and RSBB contracts show different performances in terms of supply chain coordination and flexibility. The order quantity, sales price, production costs, and capital costs determine the thresholds of the different regions under the different contracts. Managers can select the contract based on their budget constraints and the performance they expect. For example, if the budget scenario is located in Region III_{BB}, the supply chain profits under the BB and the RSBB contracts are the same. The difference is that the profit allocation under the BB contract is fixed, whereas the profit can be arbitrarily allocated under the RSBB contract. The regions can also provide a guideline for the managers to change their budgets to achieve improved performance. For any budget scenario, the RSBB contract can always maximize the expected supply chain profit under budget constraints and allow for the arbitrary allocation of profit.

We discuss the information asymmetry in which budget thresholds (TB_r and TB_m) are private. We show that if Φ is determined without considering supply chain members' budgets, the members may be inclined to reveal an artificially low budget threshold. We develop the PAA approach that links profit allocation with the budgets of members. In the RSBB contract with the PAA approach, members cannot gain an advantage by misrepresenting their own levels of budget constraint.

In this paper, we show that the RSBB contract has the following advantages that provide strong practical support for its use:

(i) Under the RSBB contract, the maximum total profit can be obtained and the supply chain profit can be arbitrarily allocated between the retailer and manufacturer.
(ii) The RSBB contract requires little additional administrative costs compared to those incurred with the RS and BB contracts.
(iii) The managers can easily see the relationship between the profit and the decision variables; consequently, they can easily choose the decision variables to obtain a specified profit.

In addition, our model can be applied in two areas.

First, managers can analyze the fund flows and profit structures under the RSBB contract. When considering supply chain members' bankruptcy risks, managers seeking high earnings may also pay attention to the components of their profits. Under the RS contract, for example, the manufacturer needs to consider the retailer's bankruptcy risk because the main part of the manufacturer's revenue is from the revenue-sharing mechanism at the end of the selling season. Under the BB contract, the retailer should consider the manufacturer's bankruptcy risk because the retailer is expected to obtain buyback revenue from the manufacturer at the end of the selling season. Under our RSBB contract, supply chain managers can adjust their profit structure while satisfying any budget constraints.

Second, with the decision framework, managers can design an optimal open-financing scheme to maximize the supply chain's expected profit by setting the value of β. Supply chain coordination and the optimal β can be achieved under the proposed RSBB contract. We expect that many managers under budget constraints and who now use supply chain contracts such as the RS and BB contracts would be interested in using our RSBB contract.

Our model also offers potential for several future applications with extensions. The first fruitful future application and extension involves the consideration of the risk-averse preference of supply chain members. Both the mean–variance analysis (e.g., Wei & Choi, 2010) and members' bankruptcy risks can be considered in our model. Specifically, one can determine the ways supply chain members' risk-averse preferences may influence supply chain coordination with members experiencing budget constraints. The second potential avenue involves a multi-period and multi-payment supply chain model. In the real world, supply chain members who experience budget constraints at various periods and retailers who pay on goods over a selling season face a complicated decision-making situation. They may be interested in an analysis of an optimal financial scheme based on these complications.

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Appendix A. Proofs

Proof of Lemma 1. Under a contract, the funds that flow outside the supply chain consist of $c_r q$ and $c_m q$. When $w \geqslant 0$, according to DF1, the budgets required by the retailer and the manufacturer are $(c_r + w)q$ and $(c_m - \beta w)q$, respectively, and the total budget for the supply chain is $(c_r + c_m)q + (1-\beta)wq$. Because $w \geqslant 0$, we can infer that the total budget is minimized when $\beta = 1$, and the minimum total budget is $(c_r + c_m)q$. When $w < 0$, the retailer and the manufacturer budgets are $(c_r + w)q$ and $(c_r - w)q$, respectively, and the minimum total budget for the supply chain is $(c_r + c_m)q$. □

Proof of Theorem 1. The expected profit function of the retailer under these contracts is

$$\Pi_r(\Phi, \Phi', b, w, \beta, q) = \Phi' pE\min(q, D) - (w + c_r)q + (b + \Phi' s)E(q - D)^+ - PB_r(w, \beta, q) \quad (A.1)$$

By substituting Eqs. (4) and (5) into (A.1), the retailer's expected profit is

$$\Pi_r(\Phi, \Phi', b, w, \beta, q) = \Phi pE\min(q, D) + \Phi sE(q - D)^+ - \Phi cq - \Phi PB_{sc}(w, \beta, q) = \Phi \Pi_{sc}(w, \beta, q).$$

Using the same approach, the manufacturer's expected profit is

$$\Pi_m(\Phi, \Phi', b, w, \beta, q) = (1 - \Phi)\Pi_{sc}(w, \beta, q). \qquad \square$$

Proof of Theorem 2. The expected profit function of the retailer under an RS contract is

$$\Pi_r(\Phi, w, \beta, q) = \Phi pE\min(q, D) - (w + c_r)q + \Phi sE(q - D)^+ - PB_r(w, \beta, q). \quad (A.2)$$

The expected profit function of the manufacturer under this contract is

$$\Pi_m(\Phi, w, \beta, q) = (1 - \Phi)pE\min(q, D) - (c_m - w)q + (1 - \Phi)sE(q - D)^+ - PB_m(w, \beta, q).$$

By substituting Eq. (6) into (A.2), the retailer's expected profit is

$$\Pi_r(\Phi, w, \beta, q) = \Phi pE\min(q, D) + \Phi sE(q - D)^+ - \Phi cq - \Phi PB_{sc}(w, \beta, q) = \Phi \Pi_{sc}(w, \beta, q).$$

Using the same approach, the manufacturer's expected profit is

$$\Pi_m(\Phi, w, \beta, q) = (1 - \Phi)\Pi_{sc}(w, \beta, q).$$

□

Proof of Theorem 3. The expected profit function of the retailer under a BB contract is

$$\Pi_r(\Phi, b, w, \beta, q) = pE\min(q, D) - (w + c_r)q + (b + s)E(q - D)^+ - PB_r(w, \beta, q). \quad (A.3)$$

The expected profit function of the manufacturer under this contract is

$$\Pi_m(\Phi, b, w, \beta, q) = (w - c_m)q - bE(q - D)^+ - PB_m(w, \beta, q).$$

By substituting Eqs. (7) and (8) into (A.3), the retailer's expected profit is

$$\Pi_r(\Phi, b, w, \beta, q) = \Phi pE\min(q, D) + \Phi sE(q - D)^+ - \Phi cq - \Phi PB_{sc}(w, \beta, q) = \Phi \Pi_{sc}(w, \beta, q).$$

Using the same approach, the manufacturer's expected profit is

$$\Pi_m(\Phi, b, w, \beta, q) = (1 - \Phi)\Pi_{sc}(w, \beta, q). \qquad \square$$

Proof of Property 1.

(i) Under the RS contract, with w^*, β^*, and q^*, we obtain

$$w^* q^* + PB_r(w^*, \beta^*, q^*) - \Phi PB_{sc}(w^*, \beta^*, q^*) - (\Phi c - c_r)q^* = 0 \quad (A.4)$$

Eq. (A.4) shows that there is a fixed Φ that satisfies (A.4) under the RS contract.

Under the BB contract, given w^*, β^*, and q^*, we obtain

$$w^* q^* + PB_r(w^*, \beta^*, q^*) - \Phi PB_{sc}(w^*, \beta^*, q^*) - [(1 - \Phi)p + \Phi c - c_r]q^* = 0 \quad (A.5)$$

Eq. (A.5) shows that there is a fixed Φ that satisfies (A.5) under the BB contract.

(ii) We can rewrite (A.4) and (A.5) as follows:

$$\Phi_{RS} = \frac{(w^* + c_r)q^* + PB_r(w^*, \beta^*, q^*)}{PB_{sc}(w^*, \beta^*, q^*) + cq^*} \quad \text{and}$$

$$\Phi_{BB} = \frac{(p - w^* - c_r)q^* - PB_r(w^*, \beta^*, q^*)}{(p - c)q^* - PB_{sc}(w^*, \beta^*, q^*)}.$$

To bring profits to the members, we have Φ_{RS}, $\Phi_{BB} \in [0, 1]$. If $\Phi_{RS} \leqslant 1$, we obtain

$$(w^* + c_r)q^* + PB_r(w^*, \beta^*, q^*) \leqslant PB_{sc}(w^*, \beta^*, q^*) + cq^* \quad (A.6)$$

If (A.6) holds, then

$$\Phi_{BB} = \frac{(p - w^* - c_r)q^* - PB_r(w^*, \beta^*, q^*)}{(p - c)q^* - PB_{sc}(w^*, \beta^*, q^*)} \geqslant \frac{(p - c)q^* - PB_{sc}(w^*, \beta^*, q^*)}{(p - c)q^* - PB_{sc}(w^*, \beta^*, q^*)} = 1.$$

Therefore, the RS and BB contracts can provide profits to the members simultaneously only if $w^* + PB_r(w^*, \beta^*, q^*)/q^* - PB_{sc}(w^*, \beta^*, q^*)/q^* = c_m$. In this case, the retailer receives the supply chain's profit under both of the contracts.

(iii) Under the RSBB contract, with w^*, β^*, and q^*, the constraints in (DF1) are

$$\begin{cases} (w^* + c_r)q^* \leqslant TB_r \\ (c_m - \beta^* w^*)q^* \leqslant TB_m \\ w^* + \frac{PB_r(w^*,\beta^*,q^*)}{q^*} + c_r = (\Phi' - \Phi)p + \Phi(c_r + c_m) + \frac{\Phi PB_{sc}(w^*,\beta^*,q^*)}{q^*} \\ (1-\beta^*)w^* \geqslant 0 \\ 0 \leqslant \beta^* \leqslant 1 \end{cases} \tag{A.7}$$

For any $\Phi \in [0, 1]$, we can find Φ' that satisfies

$$w^* + \frac{PB_r(w^*,\beta^*,q^*)}{q^*} + c_r = (\Phi' - \Phi)p + \Phi(c_r + c_m) + \frac{\Phi PB_{sc}(w^*,\beta^*,q^*)}{q^*}$$

Noting that $\{w^*, \beta^*, q^*\}$ satisfy $(w^* + c_r)q^* \leqslant TB_r$, $(c_m - \beta^* w^*)q^* \leqslant TB_m$, $(1-\beta^*)w^* \geqslant 0$, and $0 \leqslant \beta^* \leqslant 1$, we can find Φ' that illustrates a coordinated supply chain for any $\Phi \in [0,\ 1]$. □

Proof of Property 2. For I_1 and I_2, we obtain $PB_r(w,\beta,q) = \beta wq(I_1 - 1) + [(1-\beta)w + c_r]q(I_2 - 1)$ and $PB_m(w,\beta,q) = (c_m - \beta w)q(I_1 - 1) - (1-\beta)wq(I_2 - 1)$. Then, the supply chain's capital cost function is $PB_{sc}(w,\beta,q) = c_m q(I_1 - 1) + c_r q(I_2 - 1)$ which is independent of w and β. Therefore, the objective function is

$$Max\ \Pi_{sc}(w,\beta,q) = \Pi_{sc}(q) = pE\min(q,D) + sE(q-D)^+ - cq - PB_{sc}(q).$$

From DF1, the constraints satisfy

$$\begin{cases} (c_r + w)q \leqslant TB_r \\ (c_m - \beta w)q \leqslant TB_m \\ (1-\beta)w \geqslant 0 \\ 0 \leqslant \beta \leqslant 1 \end{cases} \tag{A.8}$$

For any $\{w, \beta, q\}$ in which $w \geqslant 0$, we can obtain a feasible solution $\{w, 1, q\}$ for which the objective value is the same. According to (A.8), we can infer that $\beta = 1$ when $w < 0$. Therefore, in (A.8), β can always be 1, and we can rewrite (A.8) as

$$\begin{cases} (c_r + w)q \leqslant TB_r \\ (c_m - w)q \leqslant TB_m \end{cases} \quad \square$$

Proof of Property 3. From Property 2, we can show that when $PB_{sc}(w,\beta,q) = PB_{sc}(q)$, β can be set to 1, and $PB_r(w,\beta,q)$ is a function of w and q; that is, $PB_r(w,q)$. From Eq. (4), we have $\Phi' = [PB_r(w,q) - \Phi PB_{sc}(q)]/(pq) + [w + \Phi(p-c) + c_r]/p$. Because $\partial PB_r(w,q)/\partial w \geqslant 0$, we infer that Φ' increases with w. From Eq. (5), b increases with Φ'. Therefore, b increases with w. □

Proof of Lemma 2. From Eq. (10), we determine that

$$\Pi'_{sc}(q^*_{EB}) = p - c_m I_1 - c_r I_2 - (p-s)F(q^*_{EB}) = 0.$$

From DF2, we can deduce a new constraint:

$$(c_r + c_m)q \leqslant TB_r + TB_m \tag{A.9}$$

For q that satisfies (A.9), we can find w that satisfies the constraints in DF2. Therefore, $q = (TB_r + TB_m)/c$ is the largest feasible q in DF2. Because $\Pi_{sc}(q)$ is increasing when $q \leqslant q^*_{EB}$, we infer that the supply chain leads to the maximum profit when $q^*_{BC} = (TB_r + TB_m)/c$. Therefore, the supply chain must utilize the total budget, $TB_r + TB_m$. Consequently, the constraints in DF2 are transformed as

$$\begin{cases} (w^*_{BC} + c_r)q^*_{BC} = TB_r \\ (c_m - w^*_{BC})q^*_{BC} = TB_m \end{cases}$$

Then, we determine that $w^*_{BC} = (TB_r c_m - TB_m c_r)/(TB_r + TB_m)$. □

Proof of Property 4.

(i) When $q = q^*_{EB}$, $G(w) = w + PB_r(w, q^*_{EB})/q^*_{EB}$. To achieve q^*_{EB}, from the constraints in DF2, we have

$$c_m - TB_m/q^*_{EB} \leqslant w \leqslant TB_r/q^*_{EB} - c_r \tag{A.10}$$

From Inequality (A.10), under the RS contract, TB_r and TB_m should satisfy

$$G(c_m - TB_m/q) \leqslant G(w) \leqslant G(TB_r/q - c_r)$$

Considering Eq. (6), we have $G(w) = \Phi c - c_r + PB_{sc}(q^*_{EB})/q^*_{EB}$ under the RS contract and

$$\frac{G\left(c_m - \frac{TB_m}{q^*_{EB}}\right) + c_r}{c + \frac{PB_{sc}(q^*_{EB})}{q^*_{EB}}} \leqslant \Phi \leqslant \frac{G\left(\frac{TB_r}{q^*_{EB}} - c_r\right) + c_r}{c + \frac{PB_{sc}(q^*_{EB})}{q^*_{EB}}} \tag{A.11}$$

We infer that if and only if $TB_r \geqslant [c_r + G^{-1}(c_m + PB_{sc}(q^*_{EB})/q^*_{EB})]q^*_{EB}$ and $TB_m \geqslant [c_m - G^{-1}(-c_r)]q^*_{EB}$, the RS contract can arbitrarily allocate the profit.

(ii) Letting q' be the quantity of unsold products, we infer that the supply chain profit is $p(q^*_{EB} - q') + sq' - cq^*_{EB} - PB_{sc}(q^*_{EB})$ that is greater than 0. Because $p > s$, we determine that $pq^*{}_{EB} - cq^*_{EB} - PB_{sc}(q^*_{EB}) > 0$. With the same approach, we can obtain

$$\frac{p - c_r - G\left(\frac{TB_r}{q^*_{EB}} - c_r\right)}{p - c - \frac{PB_{sc}(q^*_{EB})}{q^*_{EB}}} \leqslant \Phi \leqslant \frac{p - c_r - G\left(c_m - \frac{TB_m}{q^*_{EB}}\right)}{p - c - \frac{PB_{sc}(q^*_{EB})}{q^*_{EB}}} \tag{A.12}$$

Then, we infer that if and only if $TB_m \geqslant [c_m - G^{-1}(c_m + PB - sc(q^*_{EB})/q^*_{EB})]q^*_{EB}$ and $TB_r \geqslant [c_r + G^{-1}(p - c_r)]q^*_{EB}$, the BB contract can arbitrarily allocate the profit. □

Proof of Property 5.

(i) Under the RS contract, from Inequality (A.11), we infer that if and only if $TB_r \geqslant [c_r + G^{-1}(-c_r)]q^*_{EB}$ and $TB_m \geqslant [c_m - G^{-1}(c_m + PB_{sc}(q^*_{EB})/q^*_{EB})]q^*_{EB}$, we can find $\Phi \in [0,\ 1]$ to coordinate the supply chain.

(ii) Under the BB contract, from Inequality (A.12), we infer that if and only if $TB_r \geqslant [c_r + G^{-1}(c_m + PB_{sc}(q^*_{EB})/q^*_{EB})]q^*_{EB}$ and $TB_m \geqslant [c_m - G^{-1}(p - c_r)]q^*_{EB}$, we can find $\Phi \in [0, 1]$ to coordinate the supply chain. □

Proof of Property 6.

(i) The RS contract can achieve (w^*_{BC}, q^*_{BC}) and bring profit to the retailer and the manufacturer when $0 \leqslant \Phi \leqslant 1$, where

$$\Phi = [(w^*_{BC} + c_r)q^*_{BC} + PB_r(w^*_{BC}, q^*_{BC})]/[cq^*_{BC} + PB_{sc}(q^*_{BC})].$$

From Lemma 2, we can show that $TB_r = (w^*_{BC} + c_r)q^*_{BC}$ and $TB_r + TB_m = cq^*_{BC}$. We then infer that the RS contract can coordinate the supply chain only if $TB_r \geqslant -PB_r(w^*_{BC}, q^*_{BC})$ and $TB_m \geqslant PB_r(w^*_{BC}, q^*_{BC}) - PB_{sc}(q^*_{BC})$.

(ii) The BB contract can achieve $\{w^*_{BC}, q^*_{BC}\}$ and bring profit to the retailer and the manufacturer when $0 \leqslant \Phi \leqslant 1$, where

$\Phi = [(p - w^*_{BC} - c_r)q^*_{BC} - PB_r(w^*_{BC}, q^*_{BC})]/[(p-c)q^*_{BC} - PB_{sc}(q^*_{BC})]$.

Using the same approach, we infer that the BB contract can be used to coordinate the supply chain only if $TB_r \geqslant cq^*_{BC} - PB_r(w^*_{BC}, q^*_{BC}) + PB_{sc}(q^*_{BC})$ and $TB_m \geqslant (c-p)q^*_{BC} + PB_r(w^*_{BC}, q^*_{BC})$. □

Proof of Property 7.

(i) From the proof of Property 4, under the RS contract, any Φ and q should satisfy

$$c - \frac{TB_m}{q} + \frac{PB_r\left(c_m - \frac{TB_m}{q}, q\right)}{q} \leqslant \Phi\left(c + \frac{PB_{sc}(q)}{q}\right) \leqslant \frac{TB_r}{q} + \frac{PB_r\left(\frac{TB_r}{q} - c_r, q\right)}{q} \tag{A.13}$$

From (A.13), we can infer that $TB_m - PB_r(c_m - TB_m/q, q) \geqslant (1-\Phi)cq - \Phi\ PB_{sc}(q)$ and $TB_r + PB_r\ (TB_r/q - c_r, q) \geqslant \Phi\ [cq + PB_{sc}(q)]$. Because $\partial\ PB_r(w,\ q)/\partial w \geqslant 0$, we obtain lower bounds on TB_r and TB_m that can lead to $\{\Phi, q\}$ under the RS contract.

(ii) With the same approach, under the BB contract, we can show that

$$c - \frac{TB_m}{q} + \frac{PB_r\left(c_m - \frac{TB_m}{q}, q\right)}{q} \leqslant (1-\Phi)p + \Phi\left(c + \frac{PB_{sc}(q)}{q}\right) \leqslant \frac{TB_r}{q} + \frac{PB_r\left(\frac{TB_r}{q} - c_r, q\right)}{q} \tag{A.14}$$

From (A.14), we can infer that $TB_r + PB_r\ (TB_r/q - c_r, q) \geqslant (1-\Phi)\ pq + \Phi\ [cq + PB_{sc}(q)]$ and $TB_m - PB_r(c_m - TB_m/q, q) \geqslant (1-\Phi)\ (c-p)q - \Phi\ PB_{sc}(q)$. We can obtain lower bounds on TB_r and TB_m that achieve $\{\Phi, q\}$ under the BB contract. □

Proof of Property 8. Suppose that q has any value between 0 and q^*_{EB}. From Property 7, under the RS contract, $TB_r \geqslant c_r q(I_1 - I_2)/I_1$ and $TB_m \geqslant 0$. Therefore, all the feasible budget pairs that can be used to coordinate the supply chain for q are located on the line between $(c_r(I_1 - I_2)q/I_1, (c_m I_1 + c_r I_2)q/I_1)$ and $(cq, 0)$. We can find a small ε that satisfies $q < q + \varepsilon \leqslant q^*_{EB}$. Consequently, all of the feasible budget pairs for an order quantity of $q + \varepsilon$ are located on the line between $(c_r(q+\varepsilon)(I_1 - I_2)/I_1, (c_m I_1 + c_r I_2)(q+\varepsilon)/I_1)$ and $(c(q+\varepsilon), 0)$. The points $(c_r q(I_1 - I_2)/I_1, (c_m I_1 + c_r I_2)q/I_1)$ and $(c_r(q+\varepsilon)(I_1 - I_2)/I_1, (c_m I_1 + c_r I_2)(q+\varepsilon)/I_1)$ are on the line $TB_m c_r(I_1 - I_2) = TB_r(c_m I_1 + c_r I_2)$. The points $(cq, 0)$ and $(c(q+\varepsilon), 0)$ are on the line $TB_m = 0$. We then infer that the feasible budget pairs used to coordinate the supply chain for order quantities between 0 and q^*_{EB} are located in the region between $TB_r + TB_m = (c_r + c_m)q^*_{EB}, TB_m c_r(I_1 - I_2) = TB_r(c_m I_1 + c_r I_2)$, and $TB_m = 0$.

Using the same approach, we can show that under the BB contract, the feasible budget pairs are located in the region between $TB_m = 0$, $TB_r + TB_m = (c_r + c_m)q^*_{EB}$, and $TB_m = TB_r(c_m I_1 + c_r I_2 - p)/[c_r(I_1 - I_2) + p]$. □

Proof of Property 9. Suppose that the retailer reveals a budget threshold, $TB^d_r (< TB^o_r)$ and requires a budget of $B^d_r (= TB^d_r < B^o_r)$. We discuss the case wherein $B^o_r + B^o_m = cq^*_{EB}$ and $TB^d_r + TB^o_m > cq^*_{EB}$. The proofs under other cases are similar. If the manufacturer uses a budget equal to $B^o_m + B^o_r - B^d_r, q^*_{EB}$ can be achieved and budget constraints are satisfied. In this case, the retailer and the manufacturer's profits are still $\Phi\Pi_{sc}(q^*_{EB})$ and $(1-\Phi)\ \Pi_{sc}(q^*_{EB})$. If the manufacturer reveals $TB^d_m (< B^o_m + B^o_r - B^d_r = cq^*{}_{EB} - TB^d_r < TB^o_m)$, its budget is TB^d_m. Obviously, $\Pi_{sc}(q^* \mid TB^d_r + TB^d_m) < \Pi_{sc}(q^*_{EB})$.

When $(1-\Phi)\Pi_{sc}(q^* \mid TB^d_r + TB^d_m) - O_m(TB^d_m) < (1-\Phi)\Pi_{sc}(q^*_{EB}) - O_m(B^o_m + B^o_r - B^d_r)$, the manufacturer is willing to increase its budget. In this case, the retailer's capital management cost is decreased by $O_r(B^d_r) - O_r(B^o_r)$ while its profit remains $\Phi\ \Pi_{sc}(q^*_{EB})$. Therefore, the retailer has an incentive to reveal TB^d_r. □

Proof of Lemma 3. Suppose that the retailer reveals $TB^d_r (< TB^o_r)$ and requires $B^d_r < B^o_r$.

Case 1. The manufacturer reveals $TB^d_m (< TB^o_m)$ that leads to the budget, $B^{d1}_m (< B^o_m)$. Let the manufacturer's profit under B^{d1}_m be Π^{d1}_m and we have

$$\Pi^{d1}_m = \left[1 - \Phi_F - \lambda\left(1 - L - \frac{B^{d1}_m}{B^d_r + B^{d1}_m}\right)\right]\Pi_{sc}\left(q^*\middle|TB^d_r + TB^d_m\right).$$

Case 2. The manufacturer keeps TB^o_m and let B^{d2}_m be the budget under TB^o_m. Let $q^*(TB_r, TB_m)$ be the channel-wide optimal order quantity under $\{TB_r, TB_m\}$. If $TB^d_r + TB^o_m \geqslant cq^*(TB^o_r, TB^o_m)$, then we can obtain $B^d_r + B^{d2}_m = B^o_r + B^o_m$ and $B^{d2}_m > B^o_m$. If $TB^d_r + TB^o_m < cq^*(TB^o_r, TB^o_m)$, then $B^{d2}_m = TB^o_m \geqslant B^o_m$ and $B^d_r + B^{d2}_m < B^o_r + B^o_m$. Therefore, $B^{d2}_m \geqslant B^o_m > B^{d1}_m$ and $B^d_r + B^{d1}_m < B^d_r + B^{d2}_m \leqslant B^o_r + B^o_m$.

Then, we can obtain $\Pi_{sc}(q^* \mid TB^d_r + TB^d_m) < \Pi_{sc}(q^* \mid TB^d_r + TB^o_m)$. Let the manufacturer's expected profit under B^{d2}_m be Π^{d2}_m and we get

$$\Pi^{d2}_m = \left[1 - \Phi_F - \lambda\left(1 - L - \frac{B^{d2}_m}{B^d_r + B^{d2}_m}\right)\right]\Pi_{sc}\left(q^*\middle|TB^d_r + TB^o_m\right).$$

When $\Phi(B^d_r, B^{d1}_m)$ and $\Phi(B^d_r, B^{d2}_m) \in [0,1]$, we can obtain

$$\left[1 - \Phi_F - \lambda\left(1 - L - \frac{B^{d2}_m}{B^d_r + B^{d2}_m}\right)\right]\Pi_{sc}\left(q^*\middle|TB^d_r + TB^o_m\right) - \left[1 - \Phi_F - \lambda\left(1 - L - \frac{B^{d1}_m}{B^d_r + B^{d1}_m}\right)\right]\Pi_{sc}\left(q^*\middle|TB^d_r + TB^d_m\right) \geqslant \lambda\left(\frac{B^{d2}_m}{B^d_r + B^{d2}_m} - \frac{B^{d1}_m}{B^t_r + B^{d1}_m}\right)\Pi_{sc}\left(q^*\middle|TB^d_r + TB^o_m\right) > 0$$

The difference between the manufacturer's capital management costs under these two cases is $O_m(B^{d2}_m) - O_m(B^{d1}_m)$. If λ is sufficiently large, the manufacturer is not willing to reveal $TB^d_m (< TB^o_m)$. □

Proof of Property 10. Suppose that the retailer reveals $TB^d_r < TB^o_r$ that leads to $B^d_r < B^o_r$. From Lemma 3, the manufacturer keeps TB^o_m to yield $B^d_r + B^d_m \leqslant B^o_r + B^o_m$ and $B^d_m = B^{d2}_m \geqslant B^o_m$. Let $\Pi_r(B^o_r, B^o_m)$ and $\Pi_r(B^d_r, B^d_m)$ be the retailer's expected profits under (B^o_r, B^o_m) and $\left(B^d_r, B^d_m\right)$. The difference between these two expected profits is

$$\begin{aligned}\Delta\Pi_r &= \Pi_r(B^o_r, B^o_m) - \Pi_r\left(B^d_r, B^d_m\right) \\ &= \left[\Phi_F - \lambda\left(L - \frac{B^o_r}{B^o_r + B^o_m}\right)\right]\Pi_{sc}(q^*|TB^o_r + TB^o_m) \\ &\quad - \left[\Phi_F - \lambda\left(L - \frac{B^d_r}{B^d_r + B^d_m}\right)\right]\Pi_{sc}\left(q^*\middle|TB^d_r + TB^o_m\right)\end{aligned}$$

Considering that $\Pi_{sc}(q^* \mid TB^d_r + TB^o_m) \leqslant \Pi_{sc}(q^* \mid TB^o_r + TB^o_m)$, when $\Phi(B^o_r, B^o_m)$ and $\Phi(B^d_r, B^d_m) \in [0,1]$, we can obtain

$$\Delta\Pi_r \geqslant \lambda\left(\frac{B_r^o}{B_r^o + B_m^o} - \frac{B_r^d}{B_r^d + B_m^d}\right)\Pi_{sc}\left(q^*\middle|TB_r^o + TB_m^o\right)$$

The difference between the retailer's capital management costs under these two cases is $O_r(B_r^o) - O_r(B_r^d)$. Therefore, if λ is sufficiently large, the retailer cannot gain an advantage by revealing TB_r^d. □

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