PORTFOLIO PROCUREMENT POLICIES FOR BUDGET-CONSTRAINED SUPPLY CHAINS WITH OPTION CONTRACTS AND EXTERNAL FINANCING

Benyong Hu and Xu Chen*
School of Management and Economics
University of Electronic Science and Technology of China
Chengdu, China

Felix T. S. Chan
Department of Industrial and Systems Engineering
The Hong Kong Polytechnic University
Hung Hom, Hong Kong

Chao Meng
Department of Marketing and International Business
Valdosta State University
Valdosta, USA

(Communicated by Leen Stougie)

Abstract. This study investigates a budget-constrained retailer’s optimal financing and portfolio order policies in a supply chain with option contracts. To this end, we develop two analytical models: a basic model with wholesale price contracts as the benchmark and a model with option contracts. Each model considers both the financing scenario and the no-financing scenario. Our analyses show that the retailer uses wholesale price contracts for procurement, instead of option contracts, when its budget is extremely tight. The retailer starts to use a combination of these two types of contracts when the budget constraint is relieved. As the budget increases, the retailer adjusts the procurement ratio through both types until it can implement the optimal ordering policy with an adequate budget. In addition, the condition for seeking external financing is determined by the retailer’s initial budget, financing cost, and profit margin.

1. Introduction. Products with a short shelf-life (e.g., perishable products) are becoming increasingly popular amid the accelerating pace of technology development and the increasing requirement for consumer satisfaction [37, 38]. Because of the demand uncertainty from the end market, the short shelf-life product supply chain bears a greater market risk (stock shortage or overage) than the traditional durable product supply chain, which can afford to build inventory [13, 34]. From the point of view of suppliers, an earlier retailer order is conducive to better production planning, thereby reducing production costs. However, advance orders will

2010 Mathematics Subject Classification. Primary: 90B30, 91A10; Secondary: 91B70.
Key words and phrases. Budget constraint, external financing, portfolio procurement policy, option contract, supply chain management.

*Corresponding author: Xu Chen, E-mail: xchenxchen@263.net, Tel: +86-28-83206622.
increase the retailer’s risk of shortage or overage. Therefore, the supplier’s product supply flexibility will help the retailer better respond to the demand uncertainty from the end market. Thus, the risk is transmitted to the supplier. In practice, various manufacturing enterprises are struggling with the cost increase caused by providing the flexible production and supply required to deal with sophisticated demand [18, 23].

Moreover, the Southeast Asian financial crisis, the U.S. subprime mortgage crisis, and the European debt crisis occurred in succession and tightened global financial liquidity and the disposable budgets of many affected enterprises. Meanwhile, many international enterprises’ operational costs have increased owing to fluctuating currency exchange rates and rising global energy prices, which likely make them subject to capital constraints in business planning (e.g., procurement decisions). For example, in a typical mobile-phone supply chain in China, a supplier sells mobile phones to end users via retailers. Due to insufficient cash flow, many retailers can order only a limited number of mobile phones from the supplier, even though the predicted demand is higher [15]. This capital shortage prevents an enterprise (e.g., the retailer) from implementing the optimal decision, and, more critically, its negative effect could be amplified towards the upstream. Hence, the performance of the entire supply chain is affected by the budget constraint [6]. This urgent issue has to be resolved at the supply chain level.

In this study, we resolve the aforementioned two issues (cost increase of flexible production and budget constraint) simultaneously. Order quantity-based purchase flexibility has been proven to be effective in mitigating the monetary conflict between suppliers and retailers, such as Sun Microsystems [21] and Solectron [29]. In this type of collaboration, the supplier allows the retailer to place orders more than twice such that the retailer has more order quantity flexibility and accuracy in total procurement quantity. Previous research shows that suppliers are willing to offer retailers a certain level of procurement flexibility in order to motivate them to place larger orders [19, 35]. Moreover, the production system itself has a certain flexibility that incurs few additional costs. Such low cost flexibility is limited, however [42], while retailers always seek as much flexibility as possible. To resolve the conflicting objectives of participating enterprises in the supply chain, option contracts that provide a balance between supply chain benefits and risks are becoming popular in various supply chains [1, 32]. Retailers, by paying certain costs for purchasing options, can achieve flexible procurement and reduce market risk. Suppliers can not only benefit by selling options but also reduce the risk of order uncertainty from retailers. Therefore, option contracts have received increasing attention in supply chain management, such as in Burnetas and Ritchken [2] and Chen and Shen [8], who studied a two-echelon supply chain in option contracts. These studies showed that the supplier and the manufacturer could benefit from option contracts. In a loss-averse supply chain, Liu et al. [25] and Chen et al. [9] also proved that option contracts can improve the supplier’s and retailer’s profits. Moreover, research has proven that option contracts are advantageous for decisions in the risk-sharing mechanism [39] and feedback policy [44]. Capacity reservation contracts are equivalent to option contracts [20]. Wu et al. [41] and Park and Kim [31] studied the capacity reservation problem given the optimal reservation quantity and capacity strategies for various types of supply chains in the presence of capacity options. Cachon and Larivière [4] studied a game theory-based capacity allocation mechanism when buyers’ orders exceed the supplier’s existing capacity. The proposed
mechanism induces retailers to reveal their true demand information, such that the entire supply chain can be better off. Özer and Wei [30] and Saghaian and Van Oyen [33] carried out similar research. Although the above-reviewed literature has studied option contracts from various perspectives, the effects of the retailer’s budget constraints and financing on channel members’ optimal ordering (the retailer’s problem) and production (the supplier’s problem) policies have not been discussed. Among recent works, Wang and Chen [36, 37] investigated a newsvendor’s optimal ordering policy with option contracts under demand uncertainty. However, they did not consider procurement budget constraints.

For budget constraints, the most widely adopted approach, which has also been demonstrated to be the most effective, is external financing. Proper financing can help expand a manufacturing enterprise’s production capacity [43], improve a retailing enterprise’s procurement decisions [7], and, more importantly, enhance the overall performance of the supply chain [5, 15]. Although budget constraints are quite common, the impact of financial flows in supply chain decisions is often ignored [22]. Among the limited number of works that consider budget constraints, Levaggi [24] developed a principal agent model in which the principal (e.g., a retailer) faces a binding budget constraint and showed that an incentive-compatible contract does not guarantee that the principal will be better off. Che and Gale [7] showed that a retailer’s budget constraint may make it optimal for the seller to use nonlinear pricing. Xu and Birge [43] and Dada and Hu [17] built on the newsvendor model to make optimal production decisions in the presence of budget constraints and managerial incentives and examined the relationship between the operating conditions and financial leverage. Caldentey and Haugh [6] showed that financial hedging may eliminate budget constraints and that the use of financial markets leads to contracts that induce a non-cooperative supply chain. Chen and Wan [15] analyzed the impact of financing on individual firms as well as the entire supply chain under wholesale price contracts. They showed that both firms’ decisions are related to the retailer’s initial budget. The uniqueness of our study is that we consider a two-echelon supply chain with budget constraints in option contracts and consider financing in quantifying portfolio procurement policy.

Thus, most studies on flexible production decisions assume the sufficiency of capital. Few studies on the external financing problem have considered production decisions (e.g., option contracts), as have Caldentey and Haugh [6], Caldentey and Chen [5], and Buzacott and Zhang [3]. However, our study considers both option contracts and external financing. Under budget constraints, retailers have to re-optimize their procurement policy instead of simply reducing the order quantity from the optimum without budget constraints. The decision-making problem is a constrained nonlinear programming problem, which is more complex than the problem without the budget constraint. Therefore, it is important to study procurement policy under budget constraints.

Due to the above-mentioned limitations in the existing literature, we answer the following important questions:

1. How does external financing affect the retailer’s optimal procurement policies and the supplier’s optimal production policy under a conventional wholesale price contract?

2. How do option contracts affect the retailer’s optimal procurement policy and the supplier’s optimal production policy?
(3) How do external financing and option contracts together affect the retailer’s optimal procurement policy and the supplier’s optimal production policy?

This study examines the retailer’s procurement and external financing decisions under option contracts considering procurement budget constraints. We first propose a basic model for conventional wholesale price contracts as the benchmark. Then, we propose a model by considering both option contracts and external financing. For the proposed models, we quantify (1) the retailer’s optimal procurement policies, (2) the retailer’s external financing amount (for models considering external financing), and (3) the supplier’s optimal production policy. The main contributions of this study are as follows:

(1) We develop two supply chain models that incorporate option contracts and external financing and derive the retailer’s optimal portfolio procurement policies as well as the supplier’s optimal production policies.

(2) We reveal the effects of financing and option contracts on the retailer’s optimal portfolio procurement policies. We show that the retailer prefers the combination of a large firm order and a small option purchase when the budget constraint is binding or the external financing cost is high.

(3) We also show that, if the retailer’s budget is insufficient, it adopts financing and procures products in such a quantity that its profit margin is equal to the financing cost.

The remainder of the paper is organized as follows. In Section 2, we describe the supply chain and the study’s assumptions. In Section 3, we develop a basic model with a conventional wholesale price contract. In Section 4, we present the model with external financing and the option contract. In Section 5, we discuss the effects of financing and option contracts on portfolio procurement policies. We investigate the supplier’s production policy in Section 6. Finally, we conclude our discussion and discuss future research possibilities in Section 7.

2. Model formulation and assumptions. We consider a single-period two-echelon supply chain consisting of a supplier and a retailer. The supplier produces one type of short shelf-life products. The retailer procures the products from the supplier to meet the uncertain demand from the end market. The retailer has a fixed initial budget for orders and is eligible for financing if the budget is insufficient. For the retailer’s financing request, financing agencies conduct background checks and decide if a financing service will be provided. In line with Dada and Hu [17], Caldentey and Haugh [6], and Chen and Wan [15], we assume that financing is already granted when the retailer uses the model proposed in this study. For the scenario in which the retailer cannot obtain financing, the study also provides the optimal decisions. As the production lead time is long and the selling period is short, we consider only single-period decision making for a retailer. In addition, the retailer has to make all order decisions prior to the selling season.

In this study, we develop two models to study the retailer’s optimal financing and portfolio order policies. One is a basic model that incorporates the conventional wholesale price contract; the other is a model with option contracts. The sequences of major events in the basic model and the model with option contracts are as follows. In the basic model, the retailer places a firm order to the supplier at the beginning of the production lead time with quantity \( q \). The supplier determines its optimal production policy based on the retailer’s order and delivers the ordered quantity to the retailer at the beginning of the selling season. In the model with option contracts, the retailer can place a firm order with quantity \( q^1 \) and purchase a
certain quantity of options $q^2$ from the supplier at the beginning of the production lead time. Each option gives the retailer the right (not the obligation) to buy one unit of product before the selling season, and the supplier needs to deliver the total procurement (i.e., firm order quantity and quantity of exercised options) to the retailer. The retailer’s and supplier’s unsold products are salvaged.

The parameters used in this study are given in Table 1.

**Table 1. Nomenclature**

| Notation | Description |
|----------|-------------|
| $D$      | Random variable for market demand with $D \geq 0$ |
| $f(x)$   | Probability density function for market demand |
| $F(x)$   | Cumulative distribution function for market demand, which is a continuous, strictly increasing and invertible function of $x$ with $F(x) = 0$ |
| $F^{-1}(x)$ | Inverse function of $F(x)$ |
| $p$      | Product retail price ($$/unit) |
| $c$      | Product manufacturing cost ($$/unit) |
| $s$      | Product salvage value ($$/unit) |
| $g$      | Retailer’s shortage penalty ($$/unit) |
| $w$      | Product wholesale price under wholesale price contracts ($$/unit) |
| $w_1$    | Product wholesale price under option contracts ($$/unit) |
| $b$      | Product option price ($$/unit) |
| $w_2$    | Option exercise price ($$/unit) |
| $q$      | Retailer’s order quantity in the basic model |
| $q^1$    | Retailer’s firm order quantity in the model with option contracts |
| $q^2$    | Retailer’s option order quantity in the model with option contracts |
| $q^1 + q^2$ | Retailer’s portfolio order quantity in the model with option contracts, denoted as $q^1 + q^2 = q$ |
| $Y$      | Retailer’s initial budget |
| $H$      | Retailer’s financing amount |
| $\lambda_i$ | Generalized Lagrange multiplier, $i = 1, 2, 3$ |
| $x^+$    | $x^+ = \max(0, x)$ |
| $u$      | Mean of market demand, $u = E(D)$ |
| $E(x)$   | Expected value of variable $x$ |
| $\min(x,y)$ | Minimum between $x$ and $y$ |

We assume that the retailer’s initial budget is fixed and that there is a financing opportunity if the budget is tight. The market demand information is symmetric between the supplier and the retailer.

To avoid trivialities, we make the following assumptions for modeling [8, 44]:

1. $0 < b + s \leq w_1$. This condition implies that, if the option price is too high, the retailer will not purchase options because the procurement via wholesale price contracts is more economical for the retailer. 
2. $0 < w_1 \leq w_2 + b$. This condition implies that the unit product procurement cost of a wholesale price should not exceed that in option contracts, because the supplier faces demand uncertainty in option contracts and therefore charges more to compensate for the risk caused by the uncertainty. 
3. $0 < w_2 + b \leq p + g$. This condition implies that procurement via option contracts is profitable and ensures that the retailer is willing to exercise the purchased options rather than lose the demand. 
4. $0 < s < w_1 < p$. This condition ensures that a wholesale price is profitable.

3. The basic model. We first develop a model with wholesale price contracts as the benchmark to compare with the option contract (see Section 4). In the basic model, we assume that the retailer can obtain financing when its budget is tight.
As listed in Table 1, the amount of the retailer’s financing is denoted as \( H \) with unit financing cost \( r \) (\( r > 0 \)). Because the retailer’s budget is known and the financing amount is determined by the order quantity, the financing amount is a function of the retailer’s order quantity and initial budget. We denote \( H = H(q) \). Then, the only decision variable for the retailer after introducing financing is still the order quantity \( q \) rather than the financing amount. Thus, the retailer’s expected profit \( \pi^b[H(q), q] \) with financing is

\[
\pi^b[H(q), q] = \pi^r(q) - rH(q),
\]

where

\[
\pi^r(q) = pE[\min(q, D)] + sE[(q - D)^+] - qE[(D - q)^+] - wq, \quad \text{and} \quad H(q) = wq - Y.
\]

In Equation (1), the first term on the right-hand side is the expected profit given a sufficient budget. The second term is the financing cost, determined by the financing interest rate and the total financing amount. Equation (2) can be further written as

\[
\pi^r(q) = (p + g - w)q - (p + g - s) \int_0^q F(x)dx - gu.
\]

Then, the retailer determines its order quantity by solving the following optimization problem:

\[
\max_q \pi^b[H(q), q].
\]

Before solving Problem (5), we first derive the optimal order quantity without external financing. Let \( H(q) \equiv 0 \), meaning that the retailer does not adopt financing. Then, the budget-constrained retailer optimizes its order quantity by solving the following problem:

\[
\max_{q^*} \pi^a(q) \quad \text{s.t.} \quad wq \leq Y
\]

For Problem (6), we provide the following proposition:

**Proposition 1.** \( \pi^a(q) \) is concave in \( q \) and the optimal \( q^* \) of (6) is uniquely determined by

\[
q^*_a = \min \left( F^{-1} \left( \frac{p + g - w}{p + g - s} \right), \frac{Y}{w} \right).
\]

**Proof.** The proof is trivial and omitted here.

Based on Proposition 1, we provide the following proposition for Problem (5):

**Proposition 2.** \( \pi^b[H(q), q] \) is concave in \( q \) and the optimal \( q^*_b \) and \( H = H^*_b \) of (5) are uniquely determined by

1. If \( Y < wF^{-1} \left( \frac{p + g - (1 + r)w}{p + g - s} \right) \), then \( q^*_b = F^{-1} \left( \frac{p + g - (1 + r)w}{p + g - s} \right) \) and \( H^*_b = wF^{-1} \left( \frac{p + g - (1 + r)w}{p + g - s} \right) - Y \);
2. If \( wF^{-1} \left( \frac{p + g - (1 + r)w}{p + g - s} \right) \leq Y < wF^{-1} \left( \frac{p + g - w}{p + g - s} \right) \), then \( q^*_b \equiv \frac{Y}{w} \) and \( H^*_b = 0 \);
3. If \( Y \geq wF^{-1} \left( \frac{p + g - w}{p + g - s} \right) \), then \( q^*_b = F^{-1} \left( \frac{p + g - w}{p + g - s} \right) \) and \( H^*_b = 0 \).
Proof. (1) $Y < wF^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right)$ indicates that $H > 0$ (i.e., the retailer’s initial budget is insufficient). From Equation (1), we also obtain $\frac{d\pi^e_r(q)}{dq} = p + g - (1 + r)w - (p + g - s)F(q)$ and $\frac{d\pi^b_r(q)}{dq} = -(p + g - s)f(q) < 0$, which shows that $\pi^e_r(q)$ is concave in $q$. Letting $\frac{d\pi^e_r(q)}{dq} = 0$, we obtain $q_b^* = F^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right)$. Thus, if $Y < wF^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right)$, then $H_b^* = wF^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right) - Y$.

(2) If $Y \geq wF^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right)$, we have $\frac{d\pi^e_r(q)}{dq} \leq 0$. Then, the retailer does not adopt financing, as the financing cost exceeds the expected profit rate from additional orders, that is $H_b^* = 0$. From Proposition 1, when the retailer’s budget constraint is not binding, the retailer’s optimal order policy is $q_b^* = F^{-1}\left(\frac{p+g-w}{p+g-s}\right)$. When the budget constraint is binding, the retailer’s optimal order policy is $q_b^* = \frac{Y}{w}$. Thus, we can obtain

1) If $wF^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right) \leq Y < wF^{-1}\left(\frac{p+g-w}{p+g-s}\right)$, then $q_b^* = \frac{Y}{w}$ and $H_b^* = 0$;

2) If $Y \geq wF^{-1}\left(\frac{p+g-w}{p+g-s}\right)$, then $q_b^* = F^{-1}\left(\frac{p+g-w}{p+g-s}\right)$ and $H_b^* = 0$. \hfill \Box

Proposition 2 indicates that, if the retailer’s budget is adequate or the financing cost is lower than the retailer’s profit margin, then the retailer adopts financing. On the other hand, if the retailer’s initial budget is insufficient and the financing cost is higher than the retailer’s profit margin, then the retailer does not adopt financing.

4. The model with option contracts. In this model, we extend the basic model by considering option contracts between the supplier and the retailer. Assume that the retailer can adopt financing (such as from a bank) when the budget constraint is binding. Since the retailer’s budget is known and the financing amount is determined by the order quantities, financing amount $H$ is a function of the retailer’s order quantities and initial budget. Thus, in option contracts, the retailer’s decision variables are the firm order quantity $q^1$ and the option order quantity $q^2$, which implies that $q = q^1 + q^2$. Thus, we denote $H = H(q^1, q)$, and the retailer’s profit, denoted as $\pi^e_r[H(q^1, q), q^1, q^2]$, is defined as

$$\pi^e_r[H(q^1, q), q^1, q^2] = \pi^e_r(q^1, q) - rH(q^1, q)$$

where

$$\pi^e_r(q^1, q) = pE[\min(q, D)] + sE[(q^1 - D)^+] - w_1q^1 - b(q - q^1)$$

$$- w_2E[\min((q - q^1), (D - q^1)^+)] - gE(D - q)^+,$$

and

$$H_d(q^1, q) = w_1q^1 + (b + w_2)(q - q^1) - Y.$$  \hfill (9)

Equations (9) and (10) are the retailer’s expected profit from product sale and the financing cost, respectively. Equation (9) can be further written as

$$\pi^e_r(q^1, q) = (p + g - w_1)q^1 + (p + g - w_2 - b)(q - q^1)$$

$$- (p + g - s) \int_0^{q^1} F(x)dx - (p + g - w_2) \int_{q}^{q^1} F(x)dx - gu$$  \hfill (11)

Thus, the retailer’s optimization problem can be expressed as

$$\max_{q^1, q^2} \pi^e_r[H(q^1, q), q^1, q^2]$$

\hfill (12)
To derive the optimum of Problem (12), we first provide the optimal order quantity without external financing. Let $H(q^1, q) \equiv 0$, meaning that the retailer adopts no external financing. Thus, the budget-constrained retailer optimizes its order quantity by solving the following problem:

$$
\begin{align*}
\max_{q^1, q} & \pi^*(q^1, q) \\
\text{s.t.} & \quad w_1q^1 + (b + w_2)(q - q^1) \leq Y
\end{align*}
$$

(13)

We define

$$
Y^* = w_1\bar{q}^1 + (b + w_2) (\bar{q} - q^1),
$$

(14)

where $\bar{q}^1$ and $\bar{q}$ are decided as

$$
\bar{q}^1 = F^{-1}\left(\frac{b + w_2 - w_1}{w_2 - s}\right), \quad \text{and}
$$

$$
\bar{q} = F^{-1}\left(\frac{p + g - b - w_2}{p + g - w_2}\right), \quad \text{respectively.}
$$

(15) (16) Then we have

$$
\bar{q} = F^{-1}\left(\frac{p + g - b - w_2}{p + g - w_2}\right) - F^{-1}\left(\frac{b + w_2 - w_1}{w_2 - s}\right).
$$

(17)

For Problem (13), we provide the following proposition:

**Proposition 3.** $\pi^*(q^1, q)$ is jointly concave in $q^1$ and $q$, and the optimal $q^1 = q^1^*$ and $q = q^*_c$ of (13) are uniquely determined by

$$
\begin{align*}
& (1) \text{If } Y < Y^*, \text{ then } (q^1^*, q^*_c) \text{ and } \lambda_1 \text{ satisfy } \\
& \quad F(q^1^*) = \frac{(1 + \lambda_1)(b + w_2 - w_1)}{w_2 - s} \quad \text{and} \\
& \quad F(q^*_c) = \frac{p + g - (1 + \lambda_1)(b + w_2)}{p + g - w_2};
\end{align*}
$$

(18)

$$
\begin{align*}
& (2) \text{If } Y \geq Y^*, \text{ then } q^1^* = \bar{q}^1 \text{ and } q^*_c = \bar{q}, \text{ where } \bar{q}^1 \text{ and } \bar{q} \text{ are given in Equations (15) and (16), respectively.}
\end{align*}
$$

Proof. (1) If $Y < Y^*$, which means that the retailer’s budget is insufficient, and the budget constraint is binding. In this case, the corresponding Kuhn-Tucker conditions are found as follows:

1) $\lambda_1 \left[ Y - w_1q^1 - (b + w_2)(q - q^1) \right] = 0$;
2) $\lambda_2 q^1 = 0$;
3) $\lambda_3 g = 0$;
4) $(s - w_2) F(q^1) + (w_2 - p - g) F(q) + p + g - w_1 = \lambda_1 w_1 - \lambda_2$;
5) $- (p + g - w_2) F(q) + p + g - b - w_2 = \lambda_1 (b + w_2) - \lambda_3$;
6) $q^1 \geq 0, q \geq q^1, \lambda_1 \geq 0, \lambda_2 \geq 0, \lambda_3 \geq 0$.

where $\lambda_1, \lambda_2$ and $\lambda_3$ are the generalized Lagrange multipliers.

When $q^1 = 0$ and $q^2 > 0$, then $q = q^1 + q^2 > 0$. When $q > 0$, we obtain $\lambda_3 = 0$. From Kuhn-Tucker condition 4), we obtain $F(q) = \frac{p + g - (1 + \lambda_1)(b + w_2)}{p + g - w_2}$. From Kuhn-Tucker condition 5), we obtain $F(q) = \frac{p + g - (1 + \lambda_1)(b + w_2)}{p + g - w_2}$, that is $1 + \lambda_1 = \frac{-\lambda_3}{b + w_2 - w_1}$. Then, $F(q) = \frac{p + g + \frac{b + w_2 - w_1}{b + w_2} \lambda_2}{p + g - w_2}$. By considering $F(q) \leq 1$, we obtain $\lambda_2 \leq \frac{-w_1(b + w_2 - w_1)}{b + w_2} < 0$. This contradicts Kuhn-Tucker condition 6), in other
words $\lambda_2 \leq -\frac{w_2(b+w_2-w_1)}{b+w_2} < 0$. Obviously, $q > 0$ does not hold, and $q^1 > 0$ is satisfied.

Given $q^1 > 0$ and $q = q^1 + q^2$, we have $q > 0$. If $q^1 > 0$, according to Kuhn-Tucker conditions 2) and 3), we obtain $\lambda_2 = 0$ and $\lambda_3 = 0$, respectively. Then, from Kuhn-Tucker conditions 4) and 5) and the budget constraint, we find that the retailer’s optimal procurement policy without financing $(q_c^1, q_c^*)$ and $\lambda_1$ satisfy

\[
\begin{align*}
& w_1q_c^1 + (b + w_2) \left(q_c^* - q_c^1\right) = Y \\
& F \left(q_c^1\right) = \frac{(1 + \lambda_1)(b + w_2 - w_1)}{w_2 - s} \\
& F \left(q_c^*\right) = \frac{p + g - (1 + \lambda_1)(b + w_2)}{p + g - w_2}.
\end{align*}
\]

(2) If $Y \geq Y^*$, which means that the retailer’s budget is adequate, then the retailer’s optimal procurement policies are $q_c^1 = q^1$ and $q_c^* = q^1$, where $q^I$ and $q^1$ are given in Equations (15) and (16), respectively. \qed

Proposition 3 provides the retailer’s optimal portfolio order policies under different degrees of budget scarcity. If the retailer’s budget is sufficient (i.e., the budget constraint is not binding), then the retailer’s optimal order policies are the same as those in the case without budget constraint. If the retailer’s budget is inadequate (i.e., the budget constraint is binding), then the retailer prefers the order by product wholesale price. The order by product wholesale price is cheaper than the order in option contracts, and a certain amount of demand is always guaranteed regardless of market demand fluctuation. Thus, the retailer must not give up the cheap order mode.

Through a comparative analysis of the retailer’s optimal order policies $(q_c^1, q_c^*)$ in Proposition 3 and $(q^I, q^1)$ in Equations (15) and (16), we find that $\lambda_1$ reflects the degree of the retailer’s budget scarcity. Thus, we provide the following proposition:

Proposition 4. (1) If $\lambda_1 \geq \frac{(p+g-b-w_2)(w_2-s)-(b+w_2-w_1)(p+g-w_2)}{(b+w_2-w_1)(p+g-w_2)+(b+w_2)(w_2-s)}$, then $q_c^1 = \frac{Y}{w_1} - q_c^* = 0$; (2) If $0 < \lambda_1 < \frac{(p+g-b-w_2)(w_2-s)-(b+w_2-w_1)(p+g-w_2)}{(b+w_2-w_1)(p+g-w_2)+(b+w_2)(w_2-s)}$, then $q_c^1$ and $q_c^*$ satisfy

\[
\begin{align*}
& w_1q_c^1 + (b + w_2) \left(q_c^* - q_c^1\right) = Y \\
& F \left(q_c^1\right) = \frac{(1 + \lambda_1)(b + w_2 - w_1)}{w_2 - s} \\
& F \left(q_c^*\right) = \frac{p + g - (1 + \lambda_1)(b + w_2)}{p + g - w_2}.
\end{align*}
\]

Proof. From Proposition 3, we obtain $F \left(q_c^1\right) = \frac{(1 + \lambda_1)(b + w_2 - w_1)}{w_2 - s}$ and $F \left(q_c^*\right) = \frac{p + g - (1 + \lambda_1)(b + w_2)}{p + g - w_2}$. Thus, if $\lambda_1 = \frac{(p+g-b-w_2)(w_2-s)-(b+w_2-w_1)(p+g-w_2)}{(b+w_2-w_1)(p+g-w_2)+(b+w_2)(w_2-s)}$, then we have $q_c^1 = q_c^*$ and $q_c^* = 0$. That is, $q_c^1 = \frac{Y}{w_1}$, $q_c^* = q_c^*$, and $q_c^2 = 0$; if $0 < \lambda_1 < \frac{(p+g-b-w_2)(w_2-s)-(b+w_2-w_1)(p+g-w_2)}{(b+w_2-w_1)(p+g-w_2)+(b+w_2)(w_2-s)}$, then $q_c^1 > 0, q_c^* > q_c^1, q_c^2 > 0$, and satisfy

\[
\begin{align*}
& w_1q_c^1 + (b + w_2) \left(q_c^* - q_c^1\right) = Y \\
& F \left(q_c^1\right) = \frac{(1 + \lambda_1)(b + w_2 - w_1)}{w_2 - s} \\
& F \left(q_c^*\right) = \frac{p + g - (1 + \lambda_1)(b + w_2)}{p + g - w_2}.
\end{align*}
\]

\qed
Proposition 4 implies that, if \( \lambda_1 \) is large (i.e., the retailer’s initial budget is far less than needed), the retailer will give up procurement through option contracts and procure products only through the wholesale price contract, because the retailer’s budget is limited and the wholesale price contract is a cheaper procurement mode. If \( \lambda_1 \) is small (i.e., the retailer’s budget is in less shortage), the retailer will use both the wholesale price contract and option purchase to procure products from the supplier.

Figure 1 graphically demonstrates Propositions 3 and 4. When the retailer is extremely tight in budget \( (Y \leq y) \), which is \( \lambda_1 \geq (p+g-b-w_2)(w_2-s)-(b+w_2-w_1)(p+g-w_2)\), (12) it adopts only wholesale price contract for procurement; As the budget increases \( (y < Y \leq Y^*) \), the retailer adjusts the procurement ratio through wholesale price contracts and option contracts until it can implement the optimal ordering policy with an adequate budget.

Based on Proposition 3, we obtain the retailer’s financing and portfolio order policies of Problem (12) in the following proposition:

**Proposition 5.** \( \pi^* \) \[H(q^1, q), q^1, q] \] is jointly concave in \( q^1 \) and \( q \), and the optimal \( q^1 = q^1_\pi, q = q^\pi_1 \) and \( H(q^1, q) = H^\pi \) of (12) are uniquely determined by

1. If \( Y < w_1\overline{q_d} + (w_2 + b)\overline{q_d}^2 \), then \( q^1_\pi = \overline{q_d}, q^\pi_1 = \overline{q_d} \) and \( H^\pi = w_1\overline{q_d} + (w_2 + b)\overline{q_d}^2 - Y \), where \( \overline{q_d} = F^{-1}\left[\frac{r}{(1+r)(w_2+b-w_1)}\right] \), and \( \overline{q_d}^2 = \overline{q_d} - \frac{q}{q} \).

2. If \( w_1\overline{q_d} + (w_2 + b)\overline{q_d}^2 \leq Y < w_1\overline{q_t} + (w_2 + b)\overline{q_t} \), then \( q^1_\pi = \overline{q_t}, q^\pi_1 = \overline{q_t} \) and \( H^\pi = 0 \), where \( \overline{q_t} \) and \( q^\pi_1 \) are given by Proposition 3.

3. If \( Y \geq w_1\overline{q_t} + (w_2 + b)\overline{q_t} \), then \( q^1_\pi = \overline{q_t}, q^\pi_1 = \overline{q_t} \) and \( H^\pi = 0 \), where \( \overline{q_t} \) and \( \overline{q_t} \) are given in Equations (15) and (16), respectively.

**Proof.** (1) If \( Y < w_1\overline{q_d} + (w_2 + b)\overline{q_d}^2 \), then \( H > 0 \). From Equation (8), we obtain

\[
\frac{\partial^2 \pi^*}{\partial q^2} = (1+r)(w_2+b-w_1) - (w_2-s)F(q^1), \quad \frac{\partial^2 \pi^*}{\partial q^1 \partial q} = p + g - (1+r)(w_2+b) - (p + g - w_2)F(q), \quad \frac{\partial^2 \pi^*}{\partial q \partial q^1} = -(w_2-s)F(q^1) < 0,
\]

\[
\frac{\partial^2 \pi^*}{\partial q^2} = - (p + g - w_2)F(q) < 0 \quad \text{and} \quad \frac{\partial^2 \pi^*}{\partial q^1 \partial q} = \frac{\partial^2 \pi^*}{\partial q \partial q^1} = 0. \]

Because the Hessian matrix of \( \pi^* \left(q^1, q \right) \) is a negative definite, \( \pi^* \left(q^1, q \right) \) is jointly concave in \( q^1 \) and
have then the financing cost. If the retailer's profit margin increases, both the quantity procured through option contracts and the total order quantity will decrease, while the wholesale price quantity will increase. This is not difficult to understand because the unit price under the wholesale price contract is lower, and the procurement under the wholesale price contract is more economical when the retailer is tight in budget.

5. Discussion.

5.1. The effects of financing.

5.1.1. The effects of financing on the basic model. Comparing order policies between the case with financing and that without, we further obtain Proposition 6 as below.

**Proposition 6.** (1) If \( Y < wF^{-1} \left( \frac{p+g-(1+r)w}{p+g-s} \right) \), then \( q^*_f > q^*_a = \frac{Y}{w} \).

(2) If \( wF^{-1} \left( \frac{p+g-(1+r)w}{p+g-s} \right) \leq Y < wF^{-1} \left( \frac{p+g-w}{p+g-s} \right) \), then \( q^*_f = q^*_a = \frac{Y}{w} \).

(3) If \( Y \geq wF^{-1} \left( \frac{p+g-w}{p+g-s} \right) \), then \( q^*_f = q^*_a = F^{-1} \left( \frac{p+g-w}{p+g-s} \right) \).

**Proof.** (1) When \( Y < wF^{-1} \left( \frac{p+g-(1+r)w}{p+g-s} \right) \), that is \( F^{-1} \left( \frac{p+g-(1+r)w}{p+g-s} \right) > \frac{Y}{w} \), we have \( q^{k*} = F^{-1} \left( \frac{p+g-(1+r)w}{p+g-s} \right) \) according to Proposition 2. In addition, \( Y < \)
$wF^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right) < wF^{-1}\left(\frac{p+g-w}{p+g-s}\right)$ implies that the budget constraint is binding. According to Proposition 1, when the budget constraint is binding, the retailer's procurement quantity is $q^*_b = \frac{Y}{w}$. Thus, we obtain $q^*_b > q^*_a = \frac{Y}{w}$.

(2) When $wF^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right) \leq Y < wF^{-1}\left(\frac{p+g-w}{p+g-s}\right)$, we know that $q^*_a = \frac{Y}{w}$ according to Proposition 1 and that $q^*_b = \frac{Y}{w}$ according to Proposition 2, respectively. Hence, we obtain $q^*_a = q^*_b = \frac{Y}{w}$.

(3) When $Y \geq wF^{-1}\left(\frac{p+g-w}{p+g-s}\right)$, we have $q^*_c = F^{-1}\left(\frac{p+g-w}{p+g-s}\right)$ and $q^*_a = F^{-1}\left(\frac{p+g-w}{p+g-s}\right)$ according to Propositions 1 and 2, respectively, which gives $q^*_a = q^*_b = q^*_c = F^{-1}\left(\frac{p+g-w}{p+g-s}\right)$.

Proposition 6 implies that, when the retailer has a large profit margin for additional orders (e.g., $Y < wF^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right)$), it will adopt financing for a larger order quantity. When the retailer has a small profit margin for additional orders (e.g., $Y > wF^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right)$), it may not adopt financing because of the financing cost.

Because $\pi^*_c[\lambda, q]$ is concave in $q$ (see Proposition 2), by applying the optimal order quantity derived in Propositions 1 and 2 to Equations (4) and (1), respectively, we obtain that, if $Y < wF^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right)$, then $\pi^*_b(q^*_a) > \pi^*_c(q^*_a)$; and, if $Y \geq wF^{-1}\left(\frac{p+g-(1+r)w}{p+g-s}\right)$, then $\pi^*_b(q^*_c) = \pi^*_c(q^*_c)$. This means that the retailer seeks financing only when its initial budget is far less than the amount required for the optimal order quantity, and this financing is beneficial to the retailer.

5.1.2. The effects of financing on the model with option contracts. For the relationship between the retailer’s optimal portfolio order policy and the maximum expected profit, we provide the following proposition:

**Proposition 7.** (1) $\eta \geq q^*_a \geq q^*_c$, $q^*_a \leq q^*_1 < q^*_c$ and $q^*_a \geq q^*_2 \geq q^*_1$;

(2) $\pi^*_c(\eta^1, q) \geq \pi^*_b(q^*_1, q^*_a) \geq \pi^*_c(q^*_1, q^*_c)$

**Proof.** (1) From Equations (15) and (16), we obtain $F\left(\frac{q}{\eta}\right) = \frac{b+w_2-w_1}{w_2-w_1}$ and $F\left(\frac{\eta}{\eta}\right) = \frac{p+g-b-w_2}{p+g-w_2}$. According to Proposition 3, if the retailer’s budget is binding, we obtain $F\left(\frac{q^*_1}{\eta}\right) = \frac{(1+\lambda_1)(b+w_2-w_1)}{w_2-w_1}$ and $F\left(\frac{q^*_c}{\eta}\right) = \frac{p+g-(1+\lambda_1)(b+w_2)}{p+g-w_2}$. Because $\lambda_1 > 0$ and $F(x)$ are increasing functions of $x$, we have $F\left(\eta^1\right) > F\left(q^*_c\right)$ and $F\left(\frac{\eta}{\eta}\right) < F\left(\frac{\eta}{\eta}\right)$, which implies that $\eta > q^*_a$ and $\eta^1 < q^*_1$. Furthermore, because we define $\eta^2 = \eta^1 - \eta^1$, and $q^*_2 = q^*_c - q^*_a$, it follows that $q^*_1 > q^*_2$. Hence, we conclude that $\eta > q^*_c$, $q^*_a > q^*_1$, and $q^*_b > q^*_2$. According to Proposition 5, if $Y \geq w_1\eta^2 + (w_2 + b)\eta$, then $q^*_1 = q^*_1\eta^1$, $q^*_2 = q^*_c$, and $q^*_2 = q^*_c$. If $w_1\eta^2 + (w_2 + b)\eta^2 \leq Y < w_1\eta^1 + (w_2 + b)\eta$, where $q^*_t = F^{-1}\left(\frac{p+g-(1+r)w_1}{p+g-s}\right)$, $q^*_d = F^{-1}\left(\frac{p+g-(1+r)(w_2+b)}{p+g-w_2}\right)$, and $q^*_d = \frac{w_1}{w_2}q^*_d - \frac{w_2}{w_2}q^*_d$, it follows that $q^*_1 = q^*_c \geq \eta^1$, $q^*_a = \eta$, and $q^*_2 = q^*_2 < \eta^2$; if $Y < w_1\eta^2 + (w_2 + b)\eta$, we know that $\frac{\partial \pi^*_c(q^*_a)}{\partial q^*_a} > 0$ and $\frac{\partial \pi^*_b(q^*_a)}{\partial q^*_a} < 0$. Thus, the retailer will adopt financing and procure more products, which implies that $q^*_1 > q^*_c \geq \eta^1$, $q^*_a > \eta^1 \geq \eta$, and $q^*_2 < \eta^2 \leq \eta^2$. It then follows that $\eta \geq q^*_d \geq q^*_c$, $\eta^1 \geq q^*_d \geq q^*_1$, and $\eta^2 \geq q^*_d \geq q^*_2$. This completes the proof of Proposition 7(1).
5.2.1. The case without financing. Assume that $D \sim N(10000, 4000^2)$, $p = 12$, $g = 2$, $w = 8$, $s = 2$, and $r = 0.09$. We compare the option contracts model to the basic model in terms of order quantity and profit in Figure 2.

![Figure 2. The effects of option contracts without financing](image)

In Panel a, we observe that, when the budget is tight, the option contracts model uses only wholesale price contracts instead of option purchase because the wholesale price is cheaper. When the budget increases to a certain amount (still binding),
the retailer starts to reduce the procurement through the wholesale price contract and increase the option purchase. As option contracts help mitigate the effect of demand uncertainty, the option contracts model achieves more profit than the basic model, as shown in Panel b. Because of the shortage penalty, the retailer’s profit is negative in the option contracts model when the budget is limited. To reflect the trending of the retailer’s profit, this study maintains the curve in which the retailer gains negative income.

5.2.2. The case with financing. For the case with external financing, we use the same set of parameter values as for the previous case to compare the option contracts model to the basic model in terms of order quantity and profit.

![Figure 3. The effects of option contracts with financing](image)

Panel a. Order quantity comparison Panel b. Profit comparison

As displayed in Figure 3, due to the risk hedging effect of option contracts, the option contracts model has a larger total procurement quantity than the basic model (as shown in panel a). Accordingly, the profit in the option contracts model, as shown in Panel b, is higher than that in the basic model. This demonstrates the advantage of option contracts in improving the retailer’s performance in terms of order quantity and profit.

6. Suppliers production policy.

6.1. Case with wholesale price contracts. In this case, the retailer can place only one firm order. Therefore, the supplier’s best production decision is to produce the same quantity that the retailer has ordered:

\[ k^* = q^*_i, i = a, b, \] (18)

When \( i = a \), this refers to the scenario in which the retailer does not adopt financing; when \( i = b \), this refers to the scenario in which the retailer adopts financing. \( q^*_a \) and \( q^*_b \) are defined in Propositions 1 and 2 respectively.

6.2. Case with option contracts. In this case, the retailer’s procurement policy contains a firm order and an option order. The supplier must deliver the product quantity the retailer has ordered, denoted by \( \bar{k} \). Here, \( \bar{k} = q^*_i + \Delta_i, i = c, d \), and \( \Delta_i = \min \left\{ q^*_{i1}, (x - q^*_i)^+ \right\} \). \( \Delta_i \) is the additional order through the exercise of the
purchased options. Obviously, \( q_1^{1*} \leq \tilde{k} \leq q_1^{1*} + q_2^{1*} \). When \( i = c \), this refers to the scenario in which the retailer does not adopt financing; when \( i = d \), this refers to the scenario in which the retailer adopts financing.

We assume that the supplier knows the retailer’s initial budget and procurement policy. Because the retailer’s option exercise quantity is still uncertain, the supplier has to determine its production policy according to the retailer’s procurement policy in order to maximize its expected profit. We assume that the option exercise quantity \( \Delta_i \) has a continuous, differentiable, and invertible probability density function \( n(\Delta_i) \) and cumulative distribution function \( N(\Delta_i) \). \( N(\Delta_i) \) is non-negative and strictly increasing. \( N^{-1}(\cdot) \) is inverse function of \( N(\Delta_i) \).

It is known that the flexibility introduced by option contracts increases the uncertainty of the retailer’s actual order quantity. Therefore, the supplier bears higher risks in either oversupply or undersupply \([18]\). We assume that the supplier can switch between two production modes. The first is the General Production Mode, which requires a long lead time with a low production cost. The supplier can use this mode to meet the proportion of demand with a high level of certainty. The other mode is the Quick Response Mode, which is a high-cost production mode for meeting urgent demand. The supplier can use this mode to meet any demand that exceeds the production from the General Production Mode. The unit production cost under the General Production Mode and Quick Response Mode are defined as \( c \) and \((1 + \gamma)c\), \( \gamma > 0 \), respectively. The supplier should balance the quantity of production between those two modes. Therefore, the optimal production quantity under the General Production Mode should be the optimal solution to the following problem:

\[
\max_k \pi_s(\tilde{k}), \tag{19}
\]

where

\[
\pi_s(\tilde{k}) = \int_{\tilde{k} - q_1^1}^{\tilde{k} - q_1^1} \left[ w_2 t + s \left( \tilde{k} - q_1^1 - t \right) \right] n(t) \, dt \\
+ \int_{\tilde{k} - q_2^2}^{\tilde{k} - q_2^2} \left[ w_2 t - (1 + \gamma)c \left( t - \tilde{k} - q_1^1 \right) \right] n(t) \, dt + w_1 q_1^1 + b q_1^1 - c \tilde{k} \tag{20}
\]

In Equation (20), the five terms on the right-hand side are the expected profit from the General Production Mode, the expected profit from the Quick Response Mode, the expected profit from the firm order, the profit from option sale, and the production cost, respectively. For (19), we provide the following proposition:

**Proposition 8.** In option contracts, the supplier’s optimal production quantity, denoted as \( \tilde{k}^* \), is

\[
\tilde{k}^* = \begin{cases} 
q_1^{1*} + N^{-1} \left( \frac{\gamma c}{(1 + \gamma)c - s} \right), & \text{when } i = c \\
q_1^{d*} + N^{-1} \left( \frac{\gamma c}{(1 + \gamma)c - s} \right), & \text{when } i = d
\end{cases} \tag{21}
\]

**Proof.** From Equation (20), we obtain \( \frac{d\pi_s(\tilde{k})}{d\tilde{k}} = \gamma c - [(1 + \gamma)c - s] N(\tilde{k} - q_1^1) \) and \( \frac{d^2\pi_s(\tilde{k})}{d\tilde{k}^2} = -[(1 + \gamma)c - s] n(\tilde{k} - q_1^1) < 0 \); it follows that \( \pi_s(\tilde{k}) \) is concave in \( \tilde{k} \). Let \( \frac{d\pi_s(\tilde{k})}{d\tilde{k}} = 0 \); we then obtain \( \tilde{k}^* = q_1^1 + N^{-1} \left( \frac{\gamma c}{(1 + \gamma)c - s} \right) \). Additionally, Propositions 3
and 5 show that \( q^1 = q^1_* \) at \( i = c \) and \( q^1 = q^1_* \) at \( i = d \). Thus, we obtain Equation (21).

In the option contracts, Equation (21) provides a reference for the supplier’s production quantity decision. Figure 4 depicts how the supplier’s production quantity is affected by the variance of option exercise quantity and the additional cost of the Quick Response Mode. It shows that the supplier’s optimal production quantity \( \tilde{k}^* \) increases as the demand variance (i.e., \( \sigma(\Delta_i) \)) or the additional cost of the Quick Response Mode (i.e. \( \gamma c \)) increases.

\[ \tilde{k} = \frac{q^1_* c}{1 + \gamma c} - s \] when \( i = c \), where \( q^1_* c \) is provided in Proposition 3. When \( i = d \), the supplier’s optimal production quantity is \( \tilde{k}^* = q^1_* d + N^{-1} \left( \frac{\gamma c}{1 + \gamma c} - s \right) \), where \( q^1_* d \) is provided in Proposition 5.

From the preceding analyses, we find that the supplier also adopts four different production policies corresponding to the retailers four procurement policies.

7. Conclusions and future research. In this study, we have examined the retailer’s portfolio procurement policy for a supply chain with budget constraints. We have developed two analytical models to quantify the retailer’s optimal financing (considering financing) decision and portfolio order policies given budget constraints: a basic model with wholesale price contracts and a model with option contracts. We show that, when the retailer is in extremely short of budget, it makes procurement only through wholesale price contracts. As the budget increases, the retailer adjusts the procurement ratio through wholesale price contracts and option contracts until it can implement the optimal ordering policy for an adequate budget. In addition, the retailer starts to adopt external financing only when the condition for seeking financing is satisfied, and the condition is a function of the retailer’s initial budget, financing cost, and profit margin.

In future studies, the loss aversion behavior of supply chain members should be included. The literature has demonstrated that enterprises have shown loss aversion behaviors during decision making \([16, 28]\) and that the sensitivity of gain is less than that of loss \([9, 40]\). Therefore, loss aversion should be considered to study
portfolio procurement policies for the problem settings examined in this study. In this paper, we assume that the supplier is the Stackelberg leader and the retailer is the Stackelberg follower. Another interesting direction is considering different supply chain power structures [10, 11], such as retailer Stackelberg [12, 26] and vertical Nash [14, 27].

Acknowledgments. This research is partially supported by National Natural Science Foundation of China (No. 71272128, 71432003, 91646109).

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