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Green Credit Financing and Emission Reduction Decisions in a Retailer-Dominated Supply Chain with Capital Constraint

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Abstract: In the context of low-carbon transformation, many small and medium-sized suppliers face financial difficulties. How to encourage and motivate capital-constrained suppliers to implement low-carbon strategies has become an important problem. There is a lack of quantitative research on green financing problems in the supply chain, especially considering the bank's green credit financing (GCF) with discounted interest rates related to a low-carbon level. This paper formulates a Stackelberg game model to analyze the green financing and emission reduction decisions of a retailer-dominated supply chain consisting of one capital-constrained supplier and one capital-sufficient retailer. The retailer's environmental purchasing requirement is considered. The result shows that the retailer's procurement requirement cannot always motivate the capital-constrained supplier to improve their emission reduction rate. The mixed credit mode, which includes the bank's GCF and the retailer's partial prepayment, can help relieve the financing pressure of the capital-constrained supplier. It is found that the GCF at a discounted interest rate can effectively improve the supplier's emission reduction enthusiasm. This paper tries to provide some meaningful insights for the government and supply chain members when making sustainable strategies.

Keywords: green credit financing; prepayment; capital-constrained supplier; emission reduction; retailer-dominated

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1. Introduction

In recent years, environmental protection has become an essential requirement of economic development. In December 2020, the leaders of 27 EU Member States reached a consensus and promised to reduce greenhouse gas emissions by 55% in 2030 compared with 1990. Many countries are striving for a more sustainable economic development mode [1]. For example, the United Kingdom and the United States have issued relevant policies to achieve the net-zero target in 2050 [2,3]. Existing studies prove that digital finance can mitigate regional carbon emissions [4]. As an important means to support the green economic transformation, green credit financing (GCF) has attracted wide attention. GCF aims to encourage firms to commit to green investment [5]. In 2019, the UK released the policy of 'Green Finance Strategy', aiming to support low-carbon development through green financing. In China, the government has accelerated the transformation of the green industry and has mobilized and encouraged more social capital to invest in the green industry (http://www.gov.cn/xinwen/2016-09/03/content_5105129.htm, accessed on 10 June 2022). Since 2017, China has approved the construction of green finance pilot zones, such as Zhejiang, Guangdong, et al. In 2021, financial institutions have issued 142.5 billion yuan of carbon emission reduction loans, driving the reduction in carbon emissions by about 28.76 million tons. Now, the application of GCF in the supply chain has attracted the attention of society [6,7]. How to innovate GCF modes and optimize the operation decision scheme of the low-carbon supply chain is widely concerned in academic and industrial areas.

In reality, some retail giants, such as Walmart, Jingdong, and Suning, have dominant positions in the supply chain. They have the ability to help small and medium-sized enterprises (SMEs) relieve financing difficulties. For example, since 2017, Jingdong Finance has provided financing schemes for the whole supply chain and provided discounted interest rates for its suppliers (https://loan.jd.com/home/new/enterprise/financeInformation_2, accessed on 3 March 2022). Under the low-carbon environment, many core enterprises in the supply chain not only pay attention to their own green development but also undertake the social responsibility of the supply chain. For example, Walmart and Carrefour are committed to building a green supply chain and putting forward environmental procurement standards for suppliers. In 2019, environmental protection clauses were added to the contract terms signed by Walmart and suppliers (https://www.sohu.com/a/322876671_621691, accessed on 25 June 2022). If the products fail to meet the environmental protection requirements, the supplier will be disqualified from cooperating with Walmart.

Under the environmental pressure from core enterprises and consumers' low-carbon preferences, suppliers have to invest in low-carbon innovation. Undoubtedly, the low-carbon investment will aggravate suppliers' capital constraints [8]. In developing countries especially, most upstream suppliers are SMEs [7]. Due to the lack of sufficient funds, some suppliers are unwilling to implement low-carbon production. In addition, due to the lack of publicly available information, mortgage assets, and low credit rating, it is difficult for small suppliers to access loans from banks [9]. Therefore, the lack of financial resources may weaken the enthusiasm of capital-constrained suppliers to innovate low-carbon technologies [3,10]. How to encourage and motivate capital-constrained suppliers to implement low-carbon strategies becomes a difficult problem for the supply chain.

Now, some core enterprises in the supply chain have started to unite with financial institutions to implement green financing projects, aiming to support suppliers to provide low-carbon products. In April 2019, Walmart and HSBC jointly launched the "sustainable supply chain financing plan" to help its suppliers obtain green financing. The suppliers who participate in Walmart's "1-billion-ton emission reduction project" can apply for loans from HSBC at a discounted interest rate. Now GCF is increasingly used in projects related to green production and emission reduction [11]. Different from traditional financing, GCF focuses more on the environmental attributes of financing projects. For example, in Huzhou, China, enterprises with different green degrees will have different degrees of discounted interest rates (https://www.sohu.com/a/428367336_114986, accessed on 28 May 2022). Since May 2018, the Huzhou branch of CCB has established a green loan pricing process. It implements a floating preferential system of green loan interest rates. For the firms identified as green enterprises, the bank will provide a discount of 1–2 percentage points based on the basic interest rate (https://m.sohu.com/a/246901506_114731, accessed on 8 June 2022). Thus, in order to provide more managerial value to the capital-constrained supply chain, it is worth discussing the characteristics of GCF and the impact of GCF at a discounted interest rate on the capital-constrained supply chain.

In the academic area, though there is rich research investigating operational strategies under a low-carbon supply chain, few of them focus on GCF, especially considering the discounted interest rate related to the firms' low-carbon level. Considering the discounted interest rates in GCF will make our model more consistent with the actual situation. In this paper, supply chain finance is introduced into the low-carbon supply chain. We focus on the mixed financing mode, including the bank's GCF and the retailer's partial prepayment. This paper can provide a new perspective for the research of the low-carbon supply chain and supply chain green finance.

Based on the above background, we focus on the following three questions:

(1) Is the GCF at a discounted interest rate conducive to driving the capital-constrained supplier to implement low-carbon innovation and increase his profit?

(2) Is the retailer willing to provide partial prepayment to alleviate the supplier's financial pressure?
(3) Can mixed financing with a price-discount contract coordinate the supply chain?

To explore the above questions, this work focuses on a supply chain consisting of a supplier and a retailer. The retailer, which is a dominator in the supply chain, has environmental requirements for its supplier. We first consider a benchmark model that the supplier has sufficient funds. Then, we focus on a supply chain composed of a capital-constrained supplier and a well-funded retailer. The supplier can obtain loans through mixed financing which consists of the bank's GCF and the retailer's partial prepayment. The bank provides GCF at a discounted interest rate which is related to the emission reduction rate committed by the supply chain. We investigate how the supplier's low-carbon behaviors are affected by the mixed financing. Research results show that both the GCF and the retailer's prepayment can motivate the supplier to increase their emissions reduction rate. However, GCF is not always beneficial to the supplier's profit. GCF at a discounted interest rate is favorable for the supplier with little initial funds. In addition, the retailer's partial prepayment is not always beneficial to the retailer's profit. The retailer is expected to provide partial prepayment for the supplier who has difficulties in reducing emissions. Through numerical analysis, we discover that the pure price-discount contract under mixed financing cannot coordinate the supply chain. However, a hybrid contract of price-discount and profit-sharing can realize supply chain coordination. The above research results can help supply chain members make more scientific and reasonable decisions.

The remainder of this paper is organized as follows. Section 2 provides a brief review of the related literature. Section 3 introduces three models: the benchmark model when the supplier has sufficient funds, mixed financing without a price-discount contract, and mixed financing with a price-discount contract. In Section 4, we use numerical analysis to gain more management significance. Section 5 highlights the managerial insights obtained from the results. Section 6 concludes the paper by providing a summary of the main findings and directions for future research. All proofs of the paper are presented in Appendix A.

2. Literature Review

Due to the increasing emphasis on a sustainable economy, a low-carbon supply chain has become a hot topic in recent years. Concerning low-carbon supply chain management, many researchers are interested in operational management, the supply chain carbon footprint, and low-carbon regulations. This paper focuses on operational management in a low-carbon environment, including financing and emission reduction strategies. To highlight the contribution and innovation of our paper, we review only the literature that is representative and particularly relevant to our study, especially game theory-based models. This work provides a brief review of three research streams: operations management under a low-carbon supply chain, supply chain finance, and green finance.

2.1. Operations Management under a Low-Carbon Supply Chain

Green innovation brings new challenges to many enterprises. When considering the low-carbon environment, the operations management of supply chain participants becomes more complex [12]. Meanwhile, low-carbon supply chain management has aroused the wide attention of scholars (e.g., [13,14]).

In the research on low-carbon supply chain management, more and more studies pay attention to consumers' low-carbon preferences. Consumers who have a low-carbon preference will consider the low-carbon level of products when purchasing products. Therefore, enterprises need to balance the emission reduction investment and consumers' low-carbon demand so as to achieve more benefits. At present, some literature proves that consumers have a low-carbon preference, and this preference will influence firms' decisions [15]. On this basis, some scholars began to research the premise that consumers have low-carbon preferences. For example, Zhang et al. [16] discussed the influence of consumers' low-carbon preference on order quantity decisions and Sun et al. [17] investigated the carbon emission transfer and emission reduction problems. The results show that consumers' low-carbon preference has a positive effect on the manufacturers' carbon emission transfer level. Ghosh et al. [18] analyzed the influence of consumers' low-carbon preference on the dual-channel supply chain under cap-and-trade regulation. As consumers' low-carbon preference is an important factor affecting operational decisions of the supply chain, this paper builds a model considering consumers' low-carbon preference.

In the low-carbon environment, supply chain members are facing a dynamic and complex environment. Most of the existing literature on low-carbon supply chain management considers a supply chain composed of manufacturers and retailers, where the manufacturer is the leader. There are few articles that consider the operational problems of a retailer-dominated supply chain under a low-carbon environment. Wang et al. [12] compared the impact of three modes on the environmental and economic performances of the supply chain, including manufacturer-dominated, retailer-dominated, and no-dominator modes. Wang et al. [19] considered the carbon emission reduction decisions and coordination of the supply chain. They showed that in the retailer-dominated supply chain, the cost-sharing contract can achieve Pareto improvement. Wang et al. [20] also considered a retailer-led low-carbon supply chain. They took altruistic preference into consideration and introduced a cost-sharing contract to reach coordination. Ji and Huang [21] considered manufacturer-dominated and retailer-dominated supply chains, respectively, considering consumers' low-carbon preference and the cap-and-trade regulation. To summarize, the above literature is based on the assumption that the supply chain has sufficient funds to support its operational decisions. Now, the green procurement requirements of large retailers undoubtedly aggravate suppliers' capital constraints and, thus, have an impact on the emission reduction behavior of suppliers. Based on this, it is necessary to consider the retailer's green procurement requirement when optimizing the capital-constrained supply chain decisions.

Although the literature on firms' emission reduction decisions in the supply chain is rich, as illustrated above, most of them ignore the fact that upstream suppliers may have insufficient capital for green innovation [7]. Under a low-carbon environment, financing is a common problem faced by small and medium-sized suppliers. Therefore, how to help the capital-constrained suppliers to solve financing difficulties and improve the efficiency of the supply chain has become a concern in the academic field. In view of the shortcomings of current research, this paper discusses emission reduction decisions in a capital-constrained supply chain under the retailer's environmental procurement requirement. Such a study can enrich the theory of low-carbon supply chain management, which is helpful for guiding the operation and management of the supply chain.

2.2. Research on Supply Chain Finance

Supply chain finance is an essential topic in capital-constrained supply chains. Much published literature has analyzed the impact of different financing modes. It is also relevant to our research.

In the view of financing modes, the existing literature contains research on external financing and internal financing. A bank loan is one kind of external financing mode of the supply chain, which is widely used by capital-constrained enterprises. For example, Moretto et al. [22] analyzed the supply chain credit rating model under bank credit. Tsai [23] showed that, in China, only 23.3% of bank loans are granted to SMEs. Therefore, many SMEs have to resort to internal financing of the supply chain. Among them, trade credit is considered to be an important part of supply chain internal financing [24]. In this aspect, Lee and Rhee [25] showed that trade credit financing can encourage buyers to increase order quantities.

Within the literature on supply chain finance, most studies take note of how capital constraints and different financing modes affect supply chain decision-making and performance. For example, Gao et al. [26] assumed that manufacturers or retailers were faced with capital constraints. They mainly analyzed the impact of different capital constraints on price and order decisions. Wang et al. [27] introduced a platform financing mode and explored the financing problem of online retailers. Aljazzar et al. [28] pointed out that postponement of payment is beneficial to the environmental and economic performance of the supply chain. Zhen et al. [29] compared the effects of bank financing, third-party platform financing, and retailer trade credit financing on the pricing and financing decisions of a dual-channel supply chain. Tang and Yang [30] considered the capital-constrained fresh product supply chain. They compared the effects of bank credit, retailer delay payment, bank credit, and retailer financing on the pricing decisions of supply chain members. However, all the above-mentioned literature concerns the supply chain composed of capital-sufficient suppliers and capital-constrained retailers [31,32] or capital-sufficient manufacturers and capital-constrained retailers [9]. In fact, some large retailers are cooperating with commercial banks to provide supply chain financial services for their suppliers, such as Walmart, Jingdong, and Suning e-buy. Thus, it is necessary to consider buyer financing in a retailer-dominated supply chain.

Taking Jingdong as an example, Tunca and Zhu [33] discussed the buyer's intermediary financing mode. They mainly compared the traditional credit financing mode with the buyer's intermediary financing mode. The results showed that the buyer's intermediary financing can effectively reduce the loan interest rate and improve the efficiency of the supply chain. Deng et al. [34] discussed how the initial capital and production cost of suppliers affect the assembler's choice of the optimal financing scheme. They also made a comparative analysis of the buyer financing and bank financing modes. Reindorp et al. [35] discussed the purchase order financing mode and pointed out that, under certain conditions, the retailer is willing to help the supplier solve the financial problem by adjusting the wholesale price. Devalkar and Krishnan [36] constructed a supply chain model composed of small suppliers and large buyers. Their paper concentrated on the role of trade credit in supply chain coordination.

The above literature considers the financing problem in traditional supply chains. In this paper, supply chain finance is introduced into the low-carbon supply chain. We concentrate on the effect of the mixed financing mode on the decisions and performance of the low-carbon supply chain. In addition, we innovatively assume that the loan interest rate is affected by the emission reduction level, which is more in line with the characteristics of green credit in reality. Thus, this paper can provide a new perspective for the research on the low-carbon supply chain and supply chain green finance.

2.3. Research on Green Finance

With the development of the green industry, green finance has begun to attract the attention of many scholars (e.g., [37]); and the combination of green finance and supply chain is also worth considering. In recent years, the financing problems in the low-carbon supply chain have attracted the attention of many scholars.

Yang et al. [38] analyzed the impact of three different credit strategies on the green supply chain performance. Kang et al. [39] pointed out that carbon financing can promote upstream firms to reduce carbon emissions. In addition, through the cooperation of the supply chain members, the supply chain can better meet the requirement of carbon regulation. Cao and Yu [8] discussed the capital-constrained supply chain based on cap-and-trade regulation. Their result indicates that a revenue-sharing contract is profitable for the retailer with limited capital. Cao and Yu [40] pointed out that the manufacturer can obtain more profits by mortgaging his carbon emission permits. Wu et al. [41] discussed the impact of bank financing and trade credit on decisions in the supply chain. An et al. [5] designed a green credit finance model in a supply chain and discovered that an appropriate green investment range is profitable for the chain members. Luo et al. [6] considered supplier financing and bank financing in a green supply chain. They focused on the optimal procurement decision of a capital-constrained retailer. Fang et al. [7] showed that the manufacturer is reluctant to accept the prepayment under certain conditions. Zhang and Chen [42] focused on the relationship between remanufacturing production and financing modes. Qin et al. [43] discovered that the green finance interest rates can sometimes have a positive impact on the capital-constrained manufacturer's emission reduction. However, their study did not consider the internal financing of the supply chain. In contrast, we focus on the mixed financing mode consisting of GCF and the retailer's prepayment. Tang and Yang [44] compared the impact of bank loans and early payment on a capital-constrained supply chain from the perspective of profit, environment, and social welfare.

Although the above literature focuses on green finance, which is similar to our model, their models do not consider the retailer's environmental procurement requirements and the discounted interest rate in GCF. Combining green finance with supply chain finance and considering discounted interest rates in GCF will make our model more consistent with the actual situation.

With the above analysis, it is found that there is a lack of quantitative research on simultaneously considering environmental procurement standards and the green financing mode in low-carbon supply chain management. This work considers how different green financing modes affect the operational decisions and performance of the supply chain when suppliers are responsible for green technology investment and a lack emission reduction funds. Our essential contribution is reflected in the following three aspects. First, this work analyzes a retailer-dominated supply chain and introduces green finance into the supply chain; how to encourage the capital-constrained supplier to invest in low-carbon innovation is one of the main concerns of society. Second, we focus on the case that the retailer has environmental procurement requirements on the products provided by the supplier. Mixed financing is considered, among which the pure bank credit as a special model will also be discussed in this paper. Third, our paper addresses the impact of the bank's GCF with a discounted interest rate, which is related to the supply chain's basic emission reduction rate. Considering the discounted interest rate in GCF is the crucial factor that distinguishes green supply chain finance from traditional supply chain finance, which has not been involved in previous quantitative research. This study is presented to provide some meaningful insights for the government and supply chain members.

3. Model

In this paper, we consider a supply chain consisting of a capital-constrained supplier and a capital-sufficient retailer. As a Stackelberg leader in the supply chain, the retailer has environmental protection requirements on the supplier when purchasing products. As a follower, the supplier has to implement low-carbon innovation to comply with the minimum environmental requirements.

With the enhancement of environmental awareness, an increasing number of consumers prefer purchasing low-carbon products. In our model, the consumers are assumed to have low-carbon preferences (consumers can obtain low-carbon information from the carbon footprint label [45,46]). For the supplier, emission reduction behaviors refer to improving the green level of products through technological improvement. For example, in the home appliance industry, through technological innovation, the energy consumption of home appliances can be reduced. Consumers can obtain low-carbon information through energy labels and will prefer to buy energy-saving home appliances. The supplier's low-carbon efforts are denoted as the emission reduction rate. We assume that the retailer requires his supplier to reduce carbon emissions and put forward the basic emission reduction rate requirement (τ_0). In addition to the basic emission reduction rate, the supplier can further reduce carbon emissions to attract more consumers. The additional emission rate is denoted as τ. We aim to investigate the pricing and carbon emission reduction strategies of the supply chain members under the influence of the retailer's environmental purchasing requirement and the bank's GCF. To this end, we introduce the mixed financing mode which includes the bank's GCF and the retailer's prepayment.

The parameters and decision variables of the model in this section are summarized in Table 1.

Table 1. Notations.

Model Parameters	
a	Basic market capacity
d	The market demand
π_s	Profit function of the supplier
π_r	Profit function of the retailer
p	Unit retail price
c	Supplier's cost of raw materials
τ_0	Basic emission reduction rate, $0 \leq \tau_0 < 1$
r_0	Basic loan interest rate
k	Emission reduction investment coefficient of the supplier
λ	Retailer's prepayment ratio for the supplier, $0 \leq \lambda < 1$
θ	Consumers' price sensitivity coefficient
η	Consumers' low-carbon sensitivity coefficient
β	The GCF relevant rate
φ	Discount rate of the GCF interest
α	Price discount rate
B	The supplier's initial fund
L	The supplier's amount of loan
Decision Variables	
w	Wholesale price
ρ	Retailer's marginal profit ($\rho = p - w$)
τ	Supplier's additional emission reduction rate, $0 \leq \tau < 1$

As is known, carbon emission reduction requires an abatement investment. Referring to the previous literature (see, e.g., [28,47,48]), we use a quadratic function to depict the relationship between the abatement investment and the emission reduction rate: $C(\tau) = k\tau^2/2$. Here, the parameter k is the emission reduction investment coefficient of the supplier, which reflects the difficulty of emission reduction. The abatement cost is considered a one-time investment (e.g., [49–51]). Thus, k is assumed to be significantly large. Specifically, the conditions $k > \eta^2/2\theta$ and $p \geq w \geq c$ should be satisfied to guarantee the validity of the model. Similar assumptions are common in previous literature, such as [19,30,52].

In this section, we will analyze three models: Model a is a benchmark model that the supplier has sufficient funds to reduce carbon emissions. Model b considers the case that the supplier has limited funds and the retailer is well-funded. The supplier can obtain funds through the mixed financing mode. The bank can provide GCF and charges an interest rate considering the basic emission reduction rate. In addition, the retailer can provide partial prepayment. Model c considers the capital-constrained supply chain with a price-discount contract. In this case, in order to obtain funds from the retailer's prepayment, the supplier should give a specific price discount to the retailer as a return. In the following, we utilize the superscript "$i(i = a, b, c)$" to denote Model i (i = a,b,c). We use a linear function to describe the market demand, which is described as follows.

$$d = a - \theta p + \eta(\tau_0 + \tau). \tag{1}$$

In the function, the parameter θ represents consumers' price sensitivity. In addition, the parameter η represents consumers' low-carbon preference.

3.1. Model a: Benchmark Model

First, we analyze the benchmark model that the supplier has sufficient funds to reduce carbon emissions. In this case, $L = 0$. The decision orders of the supply chain members are as follows (see Figure 1):

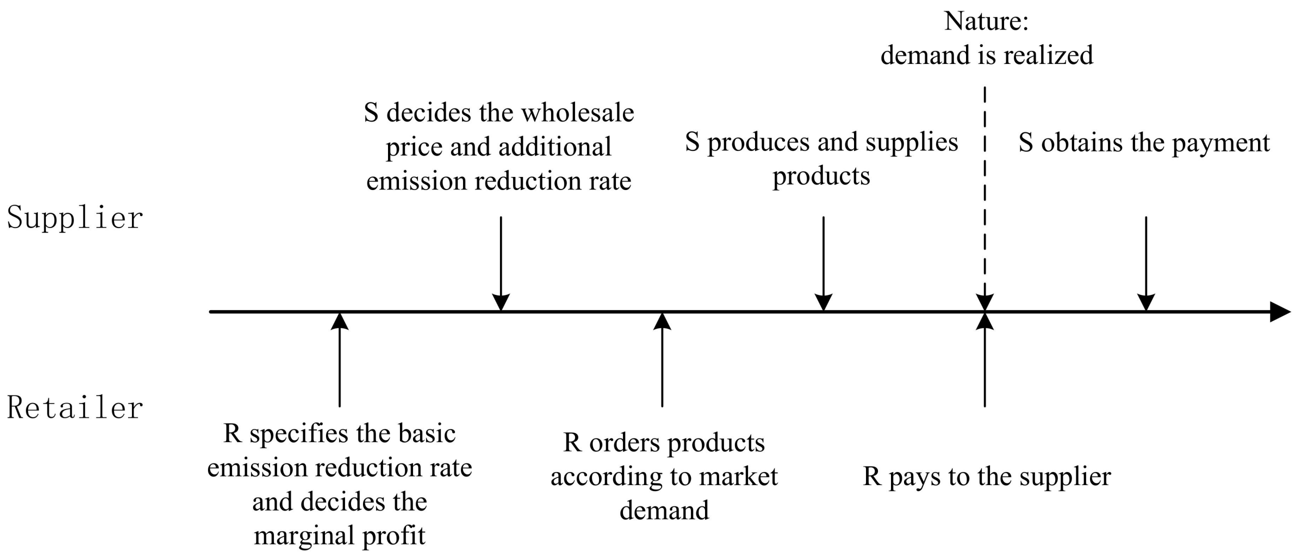


Figure 1. The sequence of events in Model a.

Stage 1: The retailer specifies the environmental procurement requirement (the basic emission reduction rate τ_0) and decides the marginal profit (ρ).

Stage 2: The supplier decides the wholesale price (w) and additional emission reduction rate (τ).

Stage 3: The retailer orders products according to market demand.

Stage 4: The supplier produces and supplies products. The retailer pays the supplier and the supplier obtains the payment.

Based on the demand functions given in Equation (1), the profits of the supplier and the retailer are as follows:

$$\pi_s^a|_{w^a,\ \tau^a} = (w^a - c)d^a - \frac{1}{2}k(\tau_0 + \tau^a)^2;\ \pi_r^a|_{\rho^a} = (p^a - w^a)d^a = \rho^a d^a. \quad (2)$$

In order to ensure that the market demand is positive when the supplier does not reduce emissions, the following condition should be satisfied: $a - c\theta > 0$. For the equilibrium solutions, we use the superscript * to denote.

Lemma 1. *For the case without capital constraint, there exist equilibrium solutions where*

$$w^{a*} = \frac{k(a+3c\theta)-2\eta^2 c}{2(2k\theta-\eta^2)},\ \tau^{a*} = \frac{\eta(a+2\eta\tau_0)-\theta(4k\tau_0+\eta c)}{2(2k\theta-\eta^2)},\ \rho^{a*} = \frac{a-\theta c}{2\theta}.$$

Based on Lemma 1, we can obtain the optimal demand and profits as follows:

$$d^{a*} = \frac{k\theta(a-c\theta)}{2(2k\theta-\eta^2)},\ \pi_s^{a*} = \frac{k(a-c\theta)^2}{8(2k\theta-\eta^2)},\ \pi_r^{a*} = \frac{k(a-c\theta)^2}{4(2k\theta-\eta^2)}.$$

3.2. Model b: Mixed Financing without Price-Discount Contract

In this section, we analyze the case where the supplier has a capital constraint. In this case, the decision orders of the supply chain members are as follows (see Figure 2):

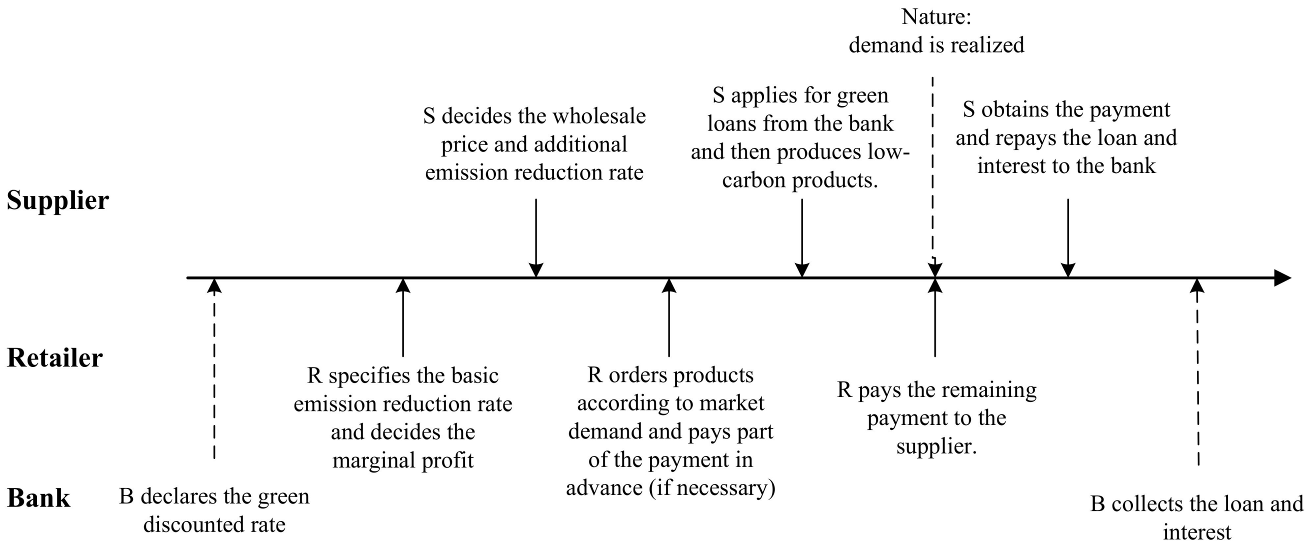


Figure 2. The sequence of events in Model b.

Stage 1: The retailer specifies the basic emission reduction rate (τ_0) and decides the marginal profit (ρ).

Stage 2: The supplier decides the wholesale price (w) and additional emission reduction rate (τ).

Stage 3: The retailer orders products according to market demand and pays part of the payment in advance (λwd), where $0 \leq \lambda < 1$. When $\lambda = 0$, it is the situation that the retailer does not pay in advance and is denoted as the pure bank credit mode.

Stage 4: The supplier applies for green loans from banks and then produces low-carbon products.

Stage 5: The retailer pays the remaining payment $(1-\lambda)wd$ to the supplier after selling the products.

Stage 6: The supplier obtains the payment and repays the loan and interest to the bank.

In this case, we consider the GCF provided by the bank. Under GCF, the bank provides discounted interest rates for green enterprises. The higher the green rating, the greater the interest rate discount. In the model, we consider the case under purchase-order financing. That is, the supplier submits financing applications to the bank by virtue of a purchase contract with the retailer. The basic emission reduction rate is specified in the contract. According to the basic emission reduction rate, the bank determines the green interest rate and provides funds to the supplier. Based on this, we assume that the green interest rate is interrelated to the basic emission reduction rate. We use a linear function to describe the green credit rate: $(1-\beta\tau_0)r_0$, where $0 \leq \beta \leq 1$. Here, r_0 is the basic loan interest rate. When $\beta = 0$, it is the case under the fixed interest rate. When $\beta > 0$, it is denoted as the case under the discounted interest rate. In order to simplify the expression, we define φ as the discount rate, where $\varphi = 1 - \beta\tau_0$ and $0 < \varphi \leq 1$.

In this case, the supplier's loan size is as follows:

$$L^b = cd^b + \frac{1}{2}k\left(\tau_0 + \tau^b\right)^2 - B - \lambda w^b d^b,\ L^b > 0. \quad (3)$$

The supplier's loan size includes four parts. The first part comes from the production costs, the second is the emission reduction cost, the third is the supplier's initial fund, and the fourth part is the payment in advance by the retailer.

Based on the demand and loan functions given in Equations (1) and (3), the profits of the chain members are as follows:

$$\pi_s^b\Big|_{w^b,\ \tau^b} = \left(w^b - c\right)d^b - \frac{1}{2}k\left(\tau_0 + \tau^b\right)^2 - \varphi r_0 L^b;\ \pi_r^b\Big|_{\rho^b} = \left(p^b - w^b\right)d^b = \rho^b d^b. \quad (4)$$

For the supplier, the profit consists of three parts. The first part is the income from selling products, the second is the emission reduction cost, and the third part is the interest of GCF. In order to ensure that the market demand is positive under pure bank credit mode, the following condition should be satisfied: $a - c\theta(1 + r_0) > 0$.

Lemma 2. *For the case under mixed financing without a price-discount, the capital-constrained supply chain exists in equilibrium solutions, where*

$$w^{b*} = \frac{k(1+\varphi r_0)[a(1+\lambda\varphi r_0)+3c\theta(1+\varphi r_0)]-2\eta^2 c(1+\varphi r_0)(1+\lambda\varphi r_0)}{2(1+\lambda\varphi r_0)[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]},$$

$$\tau^{b*} = \frac{\eta(a+2\eta\tau_0)(1+\lambda\varphi r_0)-\theta(4k\tau_0+\eta c)(1+\varphi r_0)}{2[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]},\ \rho^{b*} = \frac{a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)}{2\theta(1+\lambda\varphi r_0)}.$$

Based on the solution in Lemma 2, we can obtain the optimal demand and profits:

$$d^{b*} = \frac{\theta k(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]}{2(1+\lambda\varphi r_0)[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]},$$

$$\pi_s^{b*} = \frac{k(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]^2}{8(1+\lambda\varphi r_0)[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]} + B\varphi r_0,$$

$$\pi_r^{b*} = \frac{k(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]^2}{4(1+\lambda\varphi r_0)^2[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]}.$$

In the following, $a_i(i = 1, 2, \ldots, 5)$, $k_i(i = 1, 2, 3)$ and $B_i(i = 1, 2)$ are threshold values which are shown in Appendix A.10.

Proposition 1. $\tau^{a*} > \tau^{b*}$.

Proposition 1 is provided to show the comparison between Model a and Model b. Learning from the comparative result, it is found that the emission reduction rate in Model a is higher than that in Model b. This indicates that if the supplier has a capital constraint, he will reduce the emission reduction rate. Although GCF can provide the supplier with a discounted interest rate, the supplier's enthusiasm for emission reduction is not high due to the rising cost of capital compared with the situation in which the supplier has sufficient funds. Therefore, it is indispensable to study how to encourage the capital-constrained supplier to increase the emission reduction rate. In the following section of this paper, we focus on the impact of GCF and the retailers' prepayment and try to explore solutions to increase the supplier's emission reduction rate and profit.

To focus on the impact of the discounted interest rate on the decisions and profits of the supply chain members, we compare the case when $\beta > 0$ and $\beta = 0$ in Proposition 2.

Proposition 2. (1) $\tau^{b*}\Big|_{\beta>0} > \tau^{b*}\Big|_{\beta=0}$; (2) $\rho^{b*}\Big|_{\beta>0} > \rho^{b*}\Big|_{\beta=0}$; (3) *when* $0 < a \leq a_1$, $w^{b*}\Big|_{\beta>0} \leq w^{b*}\Big|_{\beta=0}$, $p^{b*}\Big|_{\beta>0} \leq p^{b*}\Big|_{\beta=0}$; *when* $a_1 < a \leq a_2$, $w^{b*}\Big|_{\beta>0} \leq w^{b*}\Big|_{\beta=0}$, $p^{b*}\Big|_{\beta>0} > p^{b*}\Big|_{\beta=0}$; when $a > a_2$, $w^{b*}\Big|_{\beta>0} > w^{b*}\Big|_{\beta=0}$, $p^{b*}\Big|_{\beta>0} > p^{b*}\Big|_{\beta=0}$.

Proposition 2 (1) indicates that, compared with the fixed interest rate, the discounted interest rate can encourage the supplier to improve its emission reduction rate. Under the discounted interest rate, the supplier's loan interest is lower. Thus, the supplier is willing to invest more in emission reduction through GCF. In order to improve the emission reduction rate of a capital-constrained supplier, it is necessary to implement credit incentives related to the emission reduction rate.

Proposition 2 (2) demonstrates that GCF at a discounted interest rate can improve the retailer's marginal profit. However, as is shown in Proposition 2 (3), under discounted interest rate, the wholesale price and retail price will not always increase. When the basic market capacity is relatively low ($0 < a \leq a_1$), the discounted interest rate will not only decrease the wholesale price but also decrease the retail price. When the bank implements GCF at a discounted interest rate, considering a reduction in the supplier's capital cost, the retailer will require a lower wholesale price. Due to the low market capacity, the retailer will lower prices to attract more consumers. In this case, under the GCF at a discounted interest rate, consumers can buy products with a higher emission reduction rate at a lower cost. When a falls in the range of $a_1 < a \leq a_2$, due to the increase in market capacity, the retailer gradually increases the retail price. However, in this case, due to the weak position in the supply chain, the supplier will still be required to reduce the wholesale price. At this time, part of the supplier's profit is squeezed by the retailer. When a is relatively high ($a > a_2$), implying that the market capacity is relatively large, both the supplier and the retailer will increase their selling price under the discounted interest rate. At this time, the retailer is willing to accept a higher wholesale price and transfer it to consumers through the retail price. In this case, consumers need to pay a higher price for green products.

Proposition 3. *Under pure bank credit mode* ($\lambda = 0$),

(1) $d_s^{b*}\Big|_{\beta>0} > d_s^{b*}\Big|_{\beta=0}$;

(2) *If* $B_0 < B_1$, *when* $0 \leq B < B_0$, $\pi_s^{b*}\Big|_{\beta>0} > \pi_s^{b*}\Big|_{\beta=0}$. *If* $B_0 > B_1$, *when* $0 \leq B < B_1$, $\pi_s^{b*}\Big|_{\beta>0} > \pi_s^{b*}\Big|_{\beta=0}$; *when* $B_1 \leq B < B_0$, $\pi_s^{b*}\Big|_{\beta>0} \leq \pi_s^{b*}\Big|_{\beta=0}$;

(3) *If* $0 < k < k_1$, $\pi_r^{b*}\Big|_{\beta>0} < \pi_r^{b*}\Big|_{\beta=0}$; *if* $k \geq k_1$, $\pi_r^{b*}\Big|_{\beta>0} \geq \pi_r^{b*}\Big|_{\beta=0}$.

Proposition 3 analyzes a special case in which the retailer does not provide prepayment, which is regarded as the pure bank credit mode. We compare the discounted interest rate case with the fixed interest rate case from the perspective of market demand and profits. With Proposition 3, we know that, compared with the fixed interest rate, the implementation of the discounted interest rate can always increase the market demand, but not always improve the chain members' profits. Combined with Proposition 2 (1) and 3 (1), we know that the discounted interest rate will motivate the supplier to increase the emission reduction rate. Affected by consumers' low-carbon preference and the increment of emission reduction rate, the market demand increases.

Proposition 2 (2) indicates that the supplier who has little initial capital ($0 \leq B < \min\{B_0, B_1\}$) prefers the discounted interest rate rather than the fixed interest rate. For the supplier with little initial capital, the implementation of a discounted interest rate is necessary. However, for the supplier with relatively high initial capital ($B_1 \leq B < B_0$), the GCF at a discounted interest rate is not beneficial for the supplier. In this case, the supplier is willing to accept the fixed interest rate.

Proposition 3 (3) shows that the implementation of discounted interest rates is not always beneficial for the retailer. When k is relatively low and satisfies $0 < k < k_1$, the retailer can gain more profits under a fixed interest rate. When k falls in the range of $k \geq k_1$, the discounted interest rate is profitable for the retailer. This result indicates that under discounted interest rates, the retailer is better off cooperating with the supplier who has difficulty in emission reduction. By contrast, under a fixed interest rate, the retailer should cooperate with the supplier who can reduce carbon emissions more easily.

In order to investigate the impact of the retailer's prepayment, we compare the following case under pure bank credit ($\lambda = 0$) and the case under mixed financing ($\lambda > 0$).

Proposition 4. (1) $\tau^{b*}\big|_{\lambda>0} > \tau^{b*}\big|_{\lambda=0}$; (2) $\rho^{b*}\big|_{\lambda>0} > \rho^{b*}\big|_{\lambda=0}$;

(3) *when* $0 < a \le a_3$, $w^{b*}\big|_{\lambda>0} \le w^{b*}\big|_{\lambda=0}$, $p^{b*}\big|_{\lambda>0} \le p^{b*}\big|_{\lambda=0}$; *when* $a_3 < a \le a_4$, $w^{b*}\big|_{\lambda>0} \le w^{b*}\big|_{\lambda=0}$, $p^{b*}\big|_{\lambda>0} > p^{b*}\big|_{\lambda=0}$; *when* $a > a_4$, $w^{b*}\big|_{\lambda>0} > w^{b*}\big|_{\lambda=0}$, $p^{b*}\big|_{\lambda>0} > p^{b*}\big|_{\lambda=0}$.

Proposition 4 is given to illustrate the impact of the retailers' prepayment on the emission reduction and pricing decisions of the chain members. Proposition 4 (1) shows that a retailer's prepayment can motivate the supplier to reduce carbon emissions. Compared with the case under pure bank credit, the mixed financing mode can help the supplier reduce the amount of loans. Due to the decline in capital cost, the supplier is willing to invest more in emission reduction.

Proposition 4 (2) shows that if the retailer provides prepayment for the supplier, the retailer's marginal profit will increase. However, it also shows (3) that the retail price does not always increase. When the market capacity is small ($0 < a \le a_3$), the supplier will reduce the wholesale price and the retail price. Due to the small scale of the market, reducing the sales price can attract more consumers to buy products. When the market demand increases gradually, the retailer will increase the retail price. When the market capacity satisfies $a_3 < a \le a_4$, the supplier still needs to lower the wholesale price to obtain the retailer's prepayment. Only when the market capacity is large enough ($a > a_4$), can the supplier transfer the cost by increasing the price.

Proposition 5. *Under fixed interest rate mode* ($\beta = 0$),

(1) $d^{b*}\big|_{\lambda>0} > d^{b*}\big|_{\lambda=0}$;

(2) *When* $0 < k \le k_2$, $\pi_s^{b*}\big|_{\lambda>0} \le \pi_s^{b*}\big|_{\lambda=0}$; *when* $k > k_2$, $\pi_s^{b*}\big|_{\lambda>0} > \pi_s^{b*}\big|_{\lambda=0}$;

(3) *When* $0 < k \le k_3$, $\pi_r^{b*}\big|_{\lambda>0} \le \pi_r^{b*}\big|_{\lambda=0}$. *When* $k > k_3$, $\pi_r^{b*}\big|_{\lambda>0} > \pi_r^{b*}\big|_{\lambda=0}$.

Proposition 5 analyzes a special case ($\beta = 0$) to compare the demand and profits of the chain members under pure bank credit mode with the mixed financing mode. The results show that the mixed financing mode can always increase market demand, but it does not always increase the profits of supply chain members. As Proposition 4 (1) shows, the retailer's prepayment can encourage the supplier to improve his emission reduction rate. Affected by the improvement of the emission reduction rate and consumers' low-carbon preference, the market demand increases. For supply chain members, whether the profit can be improved under mixed credit mode depends on the parameter k. A higher k means that it is more difficult for the supplier to reduce emissions and the supplier needs to pay more emission reduction costs. The results show that, under a high emission reduction investment coefficient, mixed credit financing is beneficial for both the supplier and the retailer. Thus, under a fixed interest rate, if it is easier for the supplier to implement emission reduction, the supplier will always choose a pure bank credit mode rather than a mixed financing mode. For the retailer, the prepayment is not always beneficial to their profit under the fixed interest rate mode. Thus, the retailer should provide prepayment for the supplier with difficulty in reducing emissions which can help themself improve their profit.

3.3. Model c: Mixed Financing with Price-Discount Contract

Model b shows that the retailer's prepayment is not always beneficial to improving his profit as well as the supplier's profit. Thus, in order to explore the long-term cooperation mode of the supply chain, we further consider mixed financing with a price-discount contract in Model c. In this case, the decision orders are as follows (see Figure 3).

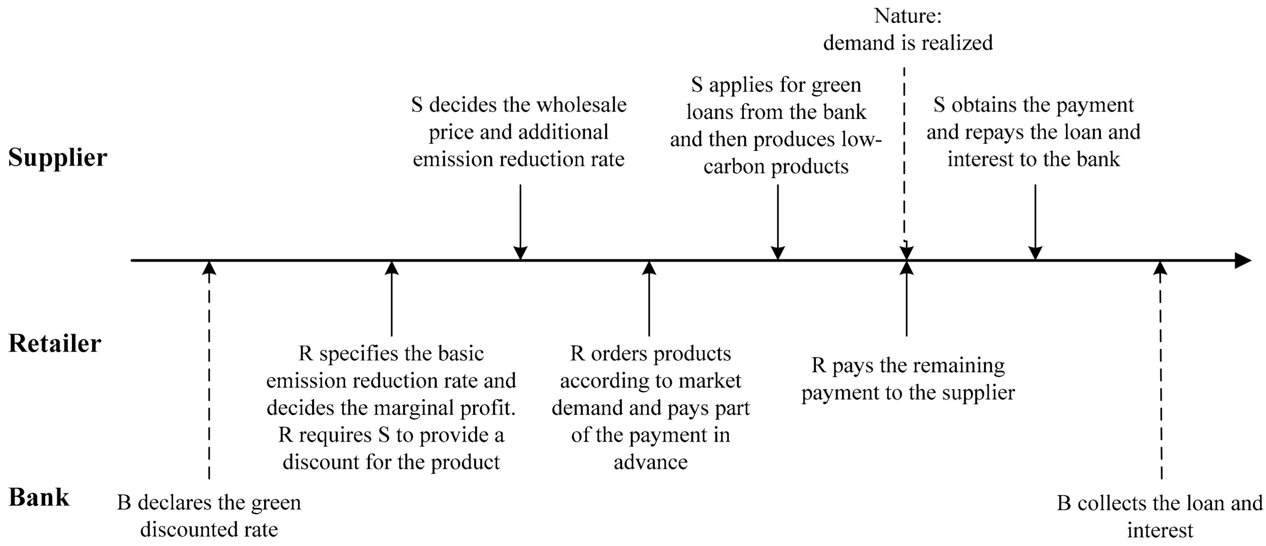


Figure 3. The sequence of events in Model c.

Stage 1: The retailer specifies the basic emission reduction rate (τ_0) and decides the marginal profit (ρ). The retailer can provide advance payment, but the supplier needs to offer a price discount rate (α) as a return.

Stage 2: The supplier decides the wholesale price (w) and additional emission reduction rate (τ).

Stage 3: The retailer orders according to market demand and pays part of the payment in advance ($\lambda \alpha w d$), where $0 < \lambda < 1$.

Stage 4: The supplier applies for green loans from the bank and then produces low-carbon products.

Stage 5: The retailer pays the remaining payment $(1-\lambda)\alpha w d$ to the supplier after selling the products.

Stage 6: The supplier obtains the payment and repays the loan and interest to the bank.

In this case, the supplier's loan size is as follows:

$$L^c = cd^c + \frac{1}{2}k(\tau_0 + \tau^c)^2 - B - \lambda \alpha w^c d^c,\ L^c > 0. \tag{5}$$

Based on the demand and loan functions given in Equations (1) and (5), the profit functions of the chain members are as follows:

$$\begin{aligned} \pi_s^c|_{w^c,\,\tau^c} &= (\alpha w^c - c)d^c - \tfrac{1}{2}k(\tau_0 + \tau^c)^2 - \varphi r_0 L^c; \\ \pi_r^c|_{\rho^c} &= (p^c - \alpha w^c)d^c = [(1-\alpha)w^c + \rho^c]d^c. \end{aligned} \tag{6}$$

Lemma 3. *For the case under mixed financing with a price-discount contract, the capital-constrained supply chain exists in equilibrium solutions, where*

$$w^{c*} = \frac{k(1+\varphi r_0)[a\alpha(1+\lambda\varphi r_0) + c\theta(2+\alpha)(1+\varphi r_0)] - 2\alpha\eta^2 c(1+\varphi r_0)(1+\lambda\varphi r_0)}{2\alpha(1+\lambda\varphi r_0)[k\theta(1+\alpha)(1+\varphi r_0) - \alpha\eta^2(1+\lambda\varphi r_0)]},$$

$$\tau^{c*} = \frac{\alpha\eta(a+2\eta\tau_0)(1+\lambda\varphi r_0) - \theta[2k\tau_0(1+\alpha) + \alpha\eta c](1+\varphi r_0)}{2[k\theta(1+\alpha)(1+\varphi r_0) - \alpha\eta^2(1+\lambda\varphi r_0)]},$$

$$\rho^{c*} = \frac{a\alpha^2(1+\lambda\varphi r_0)\left[2k\theta(1+\varphi r_0) - \eta^2(1+\lambda\varphi r_0)\right] - c\theta(1+\varphi r_0)\left[2k\theta(1+\varphi r_0) - \alpha\eta^2(2-\alpha)(1+\lambda\varphi r_0)\right]}{2\alpha\theta(1+\lambda\varphi r_0)[k\theta(1+\alpha)(1+\varphi r_0) - \alpha\eta^2(1+\lambda\varphi r_0)]}.$$

Based on the above solutions, we can obtain the market demand and the optimal profits of the chain members:

$$d^{c*} = \frac{\theta k(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]}{2(1+\lambda\varphi r_0)[k\theta(1+\alpha)(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]},$$

$$\pi_s^{c*} = \frac{k\alpha(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]^2\left[2k\theta(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)\right]}{8(1+\lambda\varphi r_0)[k\theta(1+\alpha)[1+\varphi r_0]-\alpha\eta^2[1+\lambda\varphi r_0]]^2} + B\varphi r_0,$$

$$\pi_r^{c*} = \frac{k(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]^2}{4(1+\lambda\varphi r_0)^2[k\theta(1+\alpha)(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]}.$$

Corollary 1. $\frac{\partial\tau^{c*}}{\partial\alpha} > 0$, $\frac{\partial d^{c*}}{\partial\alpha} < 0$, $\frac{\partial\pi_s^{c*}}{\partial\alpha} > 0$, $\frac{\partial\pi_r^{c*}}{\partial\alpha} < 0$.

Corollary 1 investigates the influence of the price discount rate (α) on the optimal decisions and profits. When $\alpha = 1$, Model c degenerates into Model b. The result indicates that the emission reduction rate increases as α increases. Therefore, under a mixed financing mode, the adoption of a price-discount contract will discourage the capital-constrained supplier from tackling low-carbon issues. As a result, the market demand also decreases. In addition, the supplier's profit increases as the discount rate increases, while the retailer's profit decreases with the rise of the discounted rate. Therefore, compared with Model b, the supplier's profit is higher while the retailer's profit is lower with Model c. Thus, a reasonable price discount will promote the cooperation of supply chain members. Due to the complexity of the analytical solution, we further analyze a numerical example to investigate whether mixed financing with a price-discount can coordinate the supply chain in Section 4.2.

4. Numerical Analysis

To gain more managerial insights, we analyze the impact of several parameters $(a, \alpha, \lambda, \beta, \tau_0, B)$ on the optimal decisions and profits. Partial parameter values used in this section are set as unchanged parameters: $k = 20$, $\theta = 0.8$, $\eta = 0.3$, $r_0 = 5.2\%$, $c = 5$.

4.1. Impact of a on the Profits

In this section, we set $\beta = 0.6$, $\alpha = 0.8$, $\tau_0 = 0.05$, $B = 0$ as unchanged parameters and vary the value of the basic market capacity (a).

Figure 4 is given to present the impact of the basic market capacity on the profits in Model b and Model c. It is observed that both the chain members' profits increase as a increases. However, the increase in the retailer's profit is larger than that of the supplier. Due to the retailer's dominant position in the supply chain, the increase in market demand contributes more to the retailer's profit.

4.2. Impact of α on the Profits

In this section, we highlight the impact of the price discount rate (α) on profits. We set $a = 40$, $\beta = 0.6$, $\tau_0 = 0.05$, and $B = 0$ as unchanged parameters and vary the value of discounted rate. In this case, if $\lambda > 0.3065$, then the supplier has enough funds after the retailer's prepayment. In order to analyze the mixed financing mode, we consider the case when $\lambda < 0.3065$. Next, we set $\lambda = 0.2$. In addition, in order to guarantee that the retailer's marginal profit is greater than 0, the price discount rate should satisfy $\alpha > 0.322$.

Figure 5 shows the variation in profit difference between Model b and Model c. The red/blue/green line shows the profit difference of the supplier/retailer/supply chain, respectively. Clearly, a decrease in α will enlarge the difference between Model b and Model c. As is shown in Corollary 1, the supplier's profit increases with an increase in a discounted rate, while the retailer's profit decreases with an increase in a discounted rate. Therefore, the three curves intersect at the point (1,0). It can be observed that the blue line is always less than 0, while the red line is always greater than 0. This result implies that the price-discount contract will reduce the supplier's profit while increasing the retailer's profit. In addition, the green line is always greater than 0. With an increase in α, the value $\pi^{c*} - \pi^{b*}$ decreases, showing that a lower discounted rate is beneficial to the supply chain's profit, but it is detrimental to the supplier's profit. Consequently, the pure price-discount contract cannot coordinate the supply chain. A profit-sharing contract is needed to realize supply chain coordination. If the supplier's profit in Model c is larger than that in Model b, then the supply chain can be coordinated. Such a condition requires the retailer to transfer part of the revenue to the supplier. In this case, both the supplier and the retailer can obtain a higher profit under the joint contract of price-discount and profit-sharing.

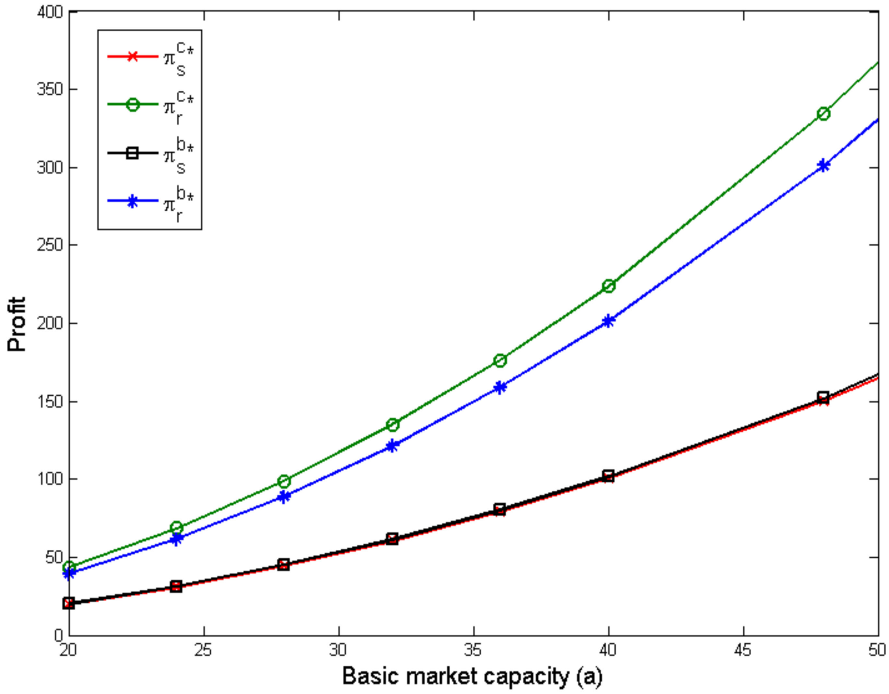


Figure 4. The supply chain members' profits as a function of basic market capacity.

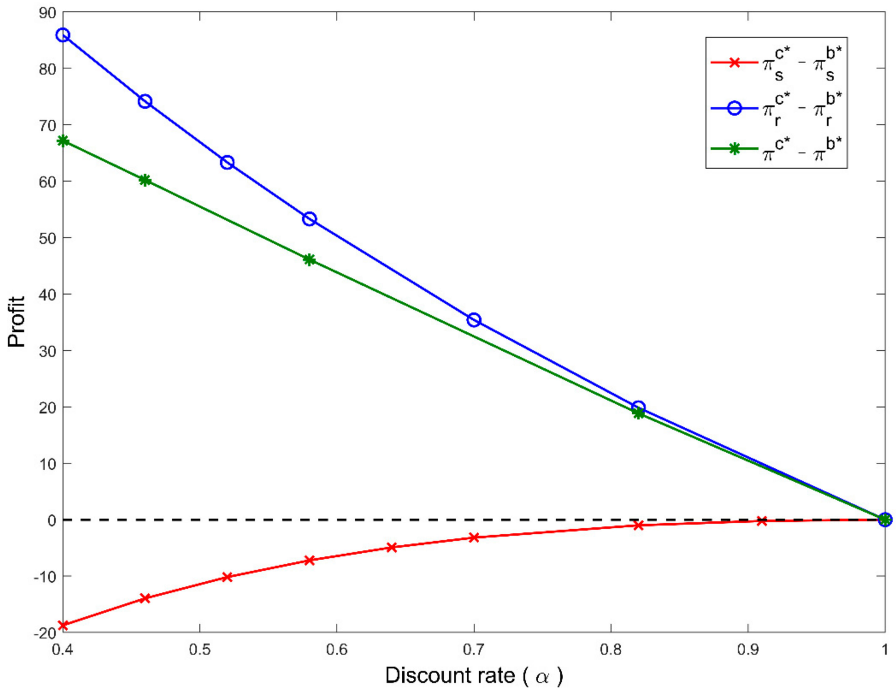


Figure 5. The comparison of profits between Model b and Model c with respect to α.

4.3. Impact of λ and β on the Emission Reduction Rate and Profits

In this section, we focus on the effect of β on the emission reduction rate and profits. We set $a = 40$, $\alpha = 0.8$, $\tau_0 = 0.05$, and $B = 0$ as unchanged parameters and vary the value of λ and β.

Figure 6 depicts the curves of the emission reduction rate in Model c with respect to parameters λ and β. Intuitively, an increase in the retailer's prepayment ratio will effectively encourage the supplier to reduce emissions. This observation is consistent with the result in Proposition 4 (1). The difference between the three curves in Figure 6 lies in the different values of the parameter β, which reflect the impact of the green discounted interest rate on the emission reduction rate. A larger β means that the supplier can obtain a lower loan interest rate under a specific emission reduction rate. Figure 6 indicates that an increase in β results in a rising in the emission reduction rate. In this case, GCF at a discounted interest rate is helpful to motivate the supplier's emission reduction enthusiasm.

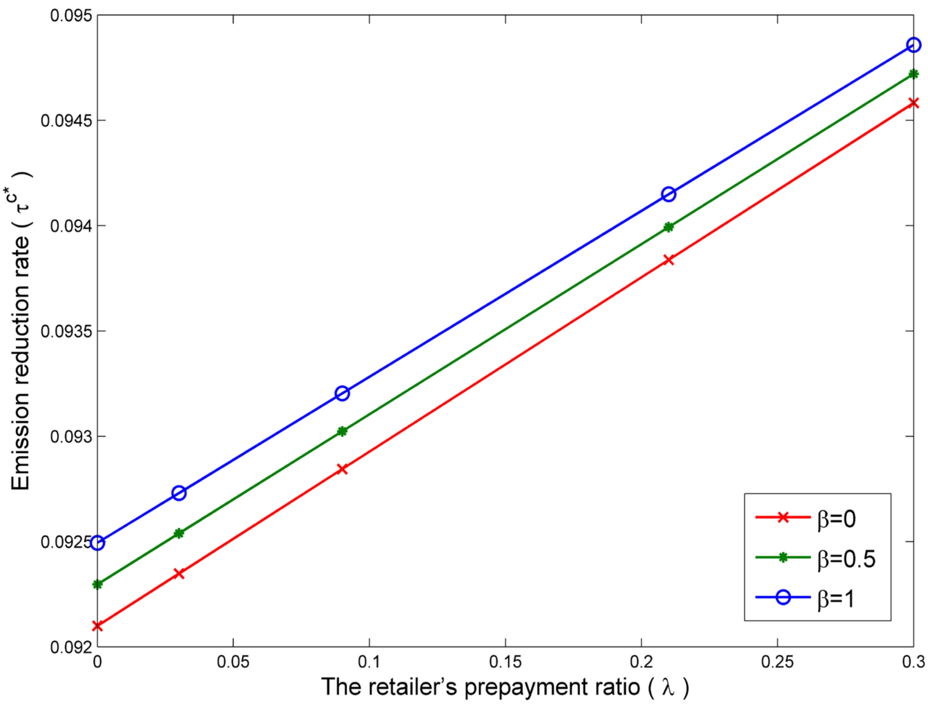
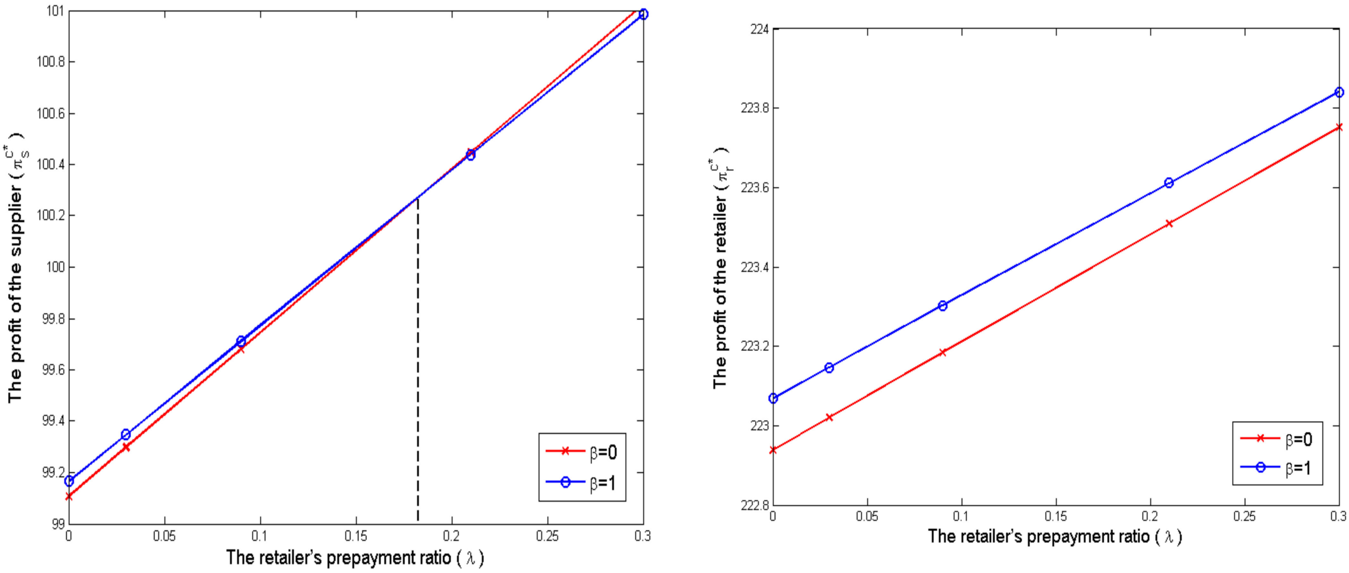


Figure 6. The relationship between emission reduction rate and λ.

Figure 7 exhibits the impact of parameters λ and β on the profits of the supplier and the retailer. Obviously, the profits of both the supplier and the retailer increase with an increase in the retailer's prepayment ratio. It can be observed from the figure that if β increases, the supplier's profit does not necessarily increase. When $\beta > 0$, it is denoted as the case under discounted interest rate; when $\beta = 0$, it is regarded as the case under fixed interest rate. This result implies that the discounted interest rate is not always profitable for the supplier. Under a small λ, an increase in β can increase the supplier's profit. As is shown in Figure 7a, when $\lambda < 0.1828$, the profit of the supplier when $\beta = 1$ is higher than that when $\beta = 0$. In this case, the loan size of the supplier is relatively large and the GCF at a discounted interest rate can help increase the supplier's profit. However, when the retailer's advance payment rate is large, the green finance cannot increase the supplier's profit. For example, Figure 7a shows that when $\lambda > 0.1828$, the supplier's profit when $\beta = 1$ is lower than that when $\beta = 0$, implying that the supplier's profit is lower when the bank provides a discounted interest rate than that when the bank provides a fixed interest rate. If the retailer's prepayment ratio is large, it can be considered that the supply chain has sufficient funds. In this case, the amount of green loans needed by suppliers is relatively low, and the fixed interest rate is more profitable for both the supplier and the retailer. When the supply chain's initial funds are insufficient, the bank is expected to provide GCF at a discounted interest rate. To some extent, these observations are consistent with the result in Proposition 3.



(**a**) the profit of the supplier (**b**) the profit of the retailer

Figure 7. The profits as a function of λ.

4.4. Impact of τ_0, β, and B on the Emission Reduction Rate and Profits

In this section, we concentrate on the effect of β on the emission reduction rate and profits. We set $a = 40$, $\alpha = 0.8$, $\tau_0 = 0.05$, and $B = 0$ as unchanged parameters and vary the value of λ and β.

In the following, we analyze a special case under pure bank credit mode ($B = 0$). In this case, the retailer does not provide the supplier with prepayment; thus, $\lambda = 0$ and $\alpha = 1$ and, consequently, Model b is the same as Model c. First, to investigate the impact of the retailer's environmental procurement requirement, we set $a = 40$ and $B = 0$ as unchanged parameters and vary the value of τ_0 and β. In Table 2, $\tau_0 + \tau^{b*}$ denotes the whole emission reduction rate of the supplier.

Table 2. Impact of the retailer's environmental procurement requirement on the emission reduction rate and profits.

τ_0	β	$\tau_0 + \tau^{b*}$	π_s^{b*}	π_r^{b*}
0	0	0.1599094537	100.3516681	200.7033362
0	0.5	0.1599094537	100.3516681	200.7033362
0	1	0.1599094537	100.3516681	200.7033362
0.05	0	0.1599094537	100.3516681	200.7033362
0.05	0.5	0.1601310971	100.3811621	200.7623242
0.05	1	0.1603532911	100.4106614	200.8213227
0.1	0	0.1599094537	100.3516681	200.7033362
0.1	0.5	0.1603532910	100.4106614	200.8213227
0.1	1	0.1607993391	100.4696757	200.9393514

With Table 2, we can make the following observations.

First, under the pure bank credit mode, when $\tau_0 = 0$, an increase in β has no influence on the supplier's emission reduction rate and chain members' profits. In this model, we assume that the GCF under the discounted interest rate is associated with the basic emission reduction rate. Therefore, if there is no environmental protection procurement standard, the implementation of a green credit-related interest rate has no effect on the emission reduction rate of the supplier and the profits of supply chain members. Secondly, when $\tau_0 > 0$, the GCF provided by the bank is conducive to improving the total emission reduction rate of the supplier; a greater β leads to a higher total emission reduction rate. In addition, the GCF is helpful to increase the supply chain members' profits. Though a higher emission reduction rate leads to a higher cost, the supplier's profit can also increase due to the profit coming from the demand expansion. Thirdly, when $\beta = 0$, there is no effect of the retailer's green procurement requirements (τ_0) on the supplier's emission reduction rate and supply chain members' profits. Therefore, it is necessary for the retailer to cooperate with banks and provide mixed credit for the capital-constrained supplier when he puts forward purchasing requirements. Fourthly, if the bank implements GCF under a discounted interest rate, the improvement of the retailer's green procurement requirements can improve the total emission reduction rate and the profits of supply chain members.

Next, we discuss the situation under pure bank credit mode. Here, we set $\tau_0 = 0.1$ and vary the value of β and B. Figure 8 is given to illustrate the impact of β and supplier's initial fund on the supplier's profit. It can be observed that the supplier's profit increases as the increases of his initial fund. In addition, the figure also shows that the GCF with a discounted interest rate is not always beneficial for the supplier. As is shown in the figure, when $B < 22.6938$, the supplier's profit when $\beta = 1$ is higher than that when $\beta = 0$. Otherwise, the supplier's profit when $\beta = 1$ is lower than that when $\beta = 0$. These results indicate that for small suppliers with limited funds, the implementation of GCF at discounted interest rate is more necessary. However, a supplier with relatively large capital will prefer the fixed interest rate. This also verifies the conclusion of Proposition 3.

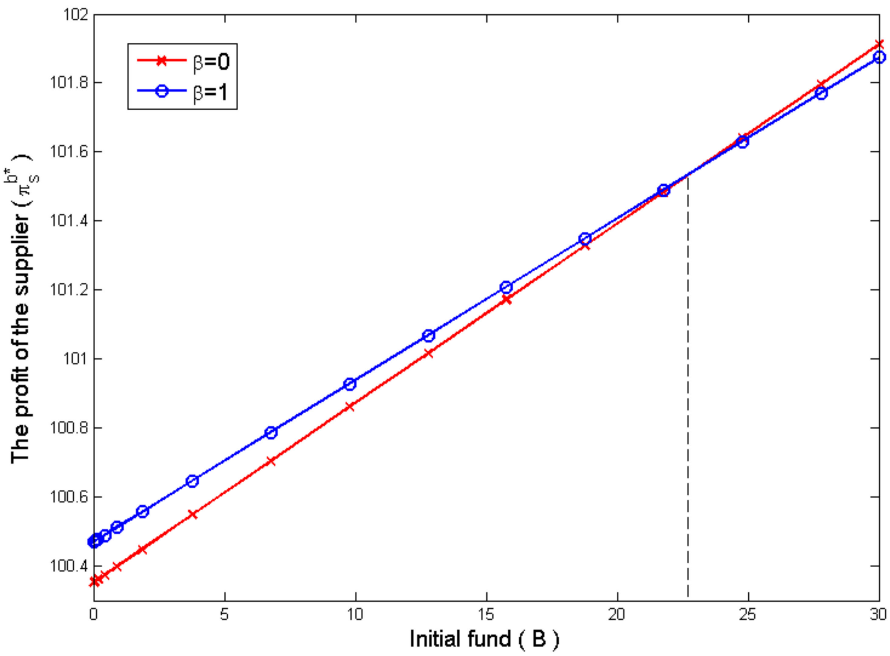


Figure 8. The supplier's profit with respect to the initial fund.

5. Managerial Insights

Our goal in this paper is to fill an existing literature gap by studying the green financing problems in supply chain management. Our main contribution lies in considering the retailer's environmental procurement requirement on the products and the bank's GCF with a discounted interest rate, which is often ignored in previous studies. Our results provide some meaningful insights for the government and supply chain members.

For the government, in order to guide low-carbon production, it is necessary to adopt financial subsidies to encourage banks to provide GCF with a discounted interest rate for suppliers with low initial capital. The GCF with a discounted interest rate can effectively motivate a capital-constrained supplier to increase their emission reduction rate. In addition, the government should strengthen low-carbon publicity and promote green consumption, so as to improve consumers' environmental awareness. The improvement of consumers' low-carbon preference can effectively motivate retailers to increase their prepayment ratio, which further motivates the capital-constrained supplier to invest more in low-carbon innovation.

For retailers, it is necessary to cooperate with banks and provide mixed credit for the capital-constrained supplier when they put forward purchasing requirements. In addition, under a discounted interest rate, the retailer is better to cooperate with a supplier who has difficulty in emission reduction. However, under a fixed interest rate, the retailer is better off cooperating with suppliers who can reduce carbon emissions more easily.

For capital-constrained suppliers, whether to apply for GCF lies in their initial capital situation. If the supplier has low initial capital, it is necessary to apply for GCF with a discounted interest rate. Under a fixed interest rate, a mixed financing mode is profitable for the supplier who has difficulty in emission reduction. By contrast, the supplier that can reduce carbon emissions more easily should choose the pure bank credit mode rather than the mixed financing mode.

6. Conclusions

This paper investigates pricing and carbon emission reduction strategies of the capital-constrained supply chain under a low-carbon environment. In our model, consumers' low-carbon preference and the retailer's green procurement requirements are both taken into account. A capital-constrained supplier and a capital-sufficient retailer are considered. The main contribution of this paper is that we take GCF and the retailer's prepayment into consideration when analyzing the supplier's low-carbon strategies.

We conclude with three main findings of this paper which can provide useful guidance for government and supply chain members to make effective strategies. (1) GCF at a discounted interest rate and a retailer's partial prepayment is effective to improve the supplier's emission reduction rate; the government is expected to support and promote the development of GCF. (2) If the retailer puts forward purchasing requirements, the mixed financing mode can help relieve the financing pressure of the capital-constrained supplier, i.e., the retailer is willing to provide a partial prepayment for a supplier who has difficulty reducing emissions. (3) The GCF with a discounted interest rate can effectively support the low-carbon transformation of a supplier who has low initial capital.

This work has several limitations and can be extended in the following directions. First, we assume that all the consumers have environmental awareness. However, some consumers are just price sensitive and unwilling to pay higher prices for low-carbon products. Thus, we can further analyze consumers' different preference behaviors. Second, we consider the model composed of one supplier and one retailer. In the model, the bank's discount rate decision is an exogenous variable, which limits the paper's contribution. In view of the real-world situation, it would be interesting to investigate the bank's discount rate decision. Third, it is worthwhile to consider the government's low-carbon policies. For example, the influence of cap-and-trade regulation and the carbon tax policy on the capital-constrained supply chain could be another area to be explored.

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Appendix A

Appendix A.1. Proof of Lemma 1

According to the converse solution, in order to obtain the equilibrium solution, we first solve the supplier's response: $\frac{\partial^2 \pi_s^a}{\partial (w^a)^2} = -2\theta < 0$, $\frac{\partial^2 \pi_s^a}{\partial w^a \partial \tau^a} = \frac{\partial^2 \pi_s^a}{\partial \tau^a \partial w^a} = \eta$, $\frac{\partial^2 \pi_s^a}{\partial (\tau^a)^2} = -k < 0$. Let H be a Hessian of π_s^a. Then $H = \begin{bmatrix} -2\theta & \eta \\ \eta & -k \end{bmatrix}$. H is a negative definite because $H_{11} < 0$. With the assumption that $2k\theta - \eta^2 > 0$, we obtain $\det(H) = 2k\theta - \eta^2 > 0$. Hence, π_s^a is concave in w^a and τ^a. Let $\partial \pi_s^a / \partial w^a = 0$ and $\partial \pi_s^a / \partial \tau^a = 0$, then we determine $w^a = \frac{k(a-\theta\rho+c\theta)-\eta^2 c}{2k\theta-\eta^2}$, $\tau^a = \frac{\eta(a-\theta\rho+\eta\tau_0)-\theta(2k\tau_0+\eta c)}{2k\theta-\eta^2}$. Then, we solve the retailer's best response. With $\frac{\partial^2 \pi_r^a}{\partial (\rho^a)^2} = -\frac{2k\theta^2}{2k\theta-\eta^2} < 0$, we can conclude that π_r^a is strictly concave in ρ^a. Let $\partial \pi_r^a / \partial \rho^a = 0$, then we can obtain $\rho^{a*} = \frac{a-\theta c}{2\theta}$. Thus we determine $w^{a*} = \frac{k(a+3c\theta)-2\eta^2 c}{2(2k\theta-\eta^2)}$, $\tau^{a*} = \frac{\eta(a+2\eta\tau_0)-\theta(4k\tau_0+\eta c)}{2(2k\theta-\eta^2)}$, $d^{a*} = \frac{k\theta(a-c\theta)}{2(2k\theta-\eta^2)}$, $\pi_s^{a*} = \frac{k(a-c\theta)^2}{8(2k\theta-\eta^2)}$, $\pi_r^{a*} = \frac{k(a-c\theta)^2}{4(2k\theta-\eta^2)}$.

Appendix A.2. Proof of Lemma 2

According to the solution of Stackelberg game equilibrium, we first solve the supplier's response: $\frac{\partial^2 \pi_s^b}{\partial (w^b)^2} = -2\theta(1+\lambda\varphi r_0) < 0$, $\frac{\partial^2 \pi_s^b}{\partial w^b \partial \tau^b} = \frac{\partial^2 \pi_s^b}{\partial \tau^b \partial w^b} = \eta(1+\lambda\varphi r_0)$, $\frac{\partial^2 \pi_s^b}{\partial (\tau^b)^2} = -k(1+\varphi r_0) < 0$. Let H be a Hessian of π_s^b. Then $H = \begin{bmatrix} -2\theta(1+\lambda\varphi r_0) & \eta(1+\lambda\varphi r_0) \\ \eta(1+\lambda\varphi r_0) & -k(1+\varphi r_0) \end{bmatrix}$. H is a negative definite because $H_{11} < 0$. With the assumption that $2k\theta - \eta^2 > 0$ and $0 \le \lambda < 1$, we can find $\det(H) = (1+\lambda\varphi r_0)\left[2k\theta(1+\varphi r_0) - \eta^2(1+\lambda\varphi r_0)\right] > 0$. Hence, π_s^b is concave in w^b and τ^b. Let $\partial \pi_s^b / \partial w^b = 0$ and $\partial \pi_s^b / \partial \tau^b = 0$, then we obtain $w^b = \frac{k(1+\varphi r_0)[(a-\theta\rho)(1+\lambda\varphi r_0)+c\theta(1+\varphi r_0)]-\eta^2 c(1+\varphi r_0)(1+\lambda\varphi r_0)}{(1+\lambda\varphi r_0)[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]}$, $\tau^b = \frac{\eta(a-\theta\rho+\eta\tau_0)(1+\lambda\varphi r_0)-\theta(2k\tau_0+\eta c)(1+\varphi r_0)}{2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)}$. Then, we solve the retailer's best response. With $\frac{\partial^2 \pi_r^b}{\partial (\rho^b)^2} = -\frac{k\theta(1+\varphi r_0)}{2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)} < 0$, we can conclude that π_r^b is strictly concave in ρ^b. Let $\partial \pi_r^b / \partial \rho^b = 0$, then we can find $\rho^{b*} = \frac{a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)}{2\theta(1+\lambda\varphi r_0)}$. Thus, we can determine

$$w^{b*} = \frac{k(1+\varphi r_0)[a(1+\lambda\varphi r_0)+3c\theta(1+\varphi r_0)]-2\eta^2 c(1+\varphi r_0)(1+\lambda\varphi r_0)}{2(1+\lambda\varphi r_0)[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]},$$

$$\tau^{b*} = \frac{\eta(a+2\eta\tau_0)(1+\lambda\varphi r_0)-\theta(4k\tau_0+\eta c)(1+\varphi r_0)}{2[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]},$$

$$d^{b*} = \frac{\theta k(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]}{2(1+\lambda\varphi r_0)[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]},$$

$$\pi_s^{b*} = \frac{k(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]^2}{8(1+\lambda\varphi r_0)[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]} + B\varphi r_0,$$

$$\pi_r^{b*} = \frac{k(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]^2}{4(1+\lambda\varphi r_0)^2[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]}.$$

Appendix A.3. Proof of Proposition 1

$$\tau^{a*} - \tau^{b*} = \frac{\eta r_0 \theta\varphi\left(2ak-c\eta^2\right)(1-\lambda)}{2(2k\theta-\eta^2)[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]} > 0.$$

Appendix A.4. Proof of Proposition 2

(1) $\tau^{b*}\Big|_{\beta>0} - \tau^{b*}\Big|_{\beta=0} = \frac{\beta\eta\theta\tau_0 r_0\left(2ak-c\eta^2\right)(1-\lambda)}{2[2k\theta(1+r_0)-\eta^2(1+\lambda r_0)][2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)]} > 0.$

(2) $\rho^{b*}\Big|_{\beta>0} - \rho^{b*}\Big|_{\beta=0} = \frac{\beta c\tau_o r_0(1-\lambda)}{2(1+\lambda r_0)(1+\lambda\varphi r_0)} > 0.$

(3)

$$w^{b*}|_{\beta>0} - w^{b*}|_{\beta=0} = \frac{\beta\tau_0 r_0(1-\lambda)\left\{\begin{array}{l}\eta^2(1+\lambda r_0)(1+\lambda\varphi r_0)\left(ak-2c\eta^2\right)- \\ 6c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]-3c\theta k\eta^2\beta\tau_0 r_0(1-\lambda)\end{array}\right\}}{2(1+\lambda\varphi r_0)(1+\lambda r_0)\left[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]\left[2k\theta(1+r_0)-\eta^2(1+\lambda r_0)\right]}.$$

Thus, when $0 < a \le \frac{6c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]+3c\theta k\eta^2\beta\tau_0 r_0(1-\lambda)+2c\eta^4(1+\lambda r_0)(1+\lambda\varphi r_0)}{\eta^2 k(1+\lambda r_0)(1+\lambda\varphi r_0)}$,

$w^{b*}\Big|_{\beta>0} \le w^{b*}\Big|_{\beta=0}$; otherwise, when

$a > \frac{6c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]+3c\theta k\eta^2\beta\tau_0 r_0(1-\lambda)+2c\eta^4(1+\lambda r_0)(1+\lambda\varphi r_0)}{\eta^2 k(1+\lambda r_0)(1+\lambda\varphi r_0)}$,

$w^{b*}\Big|_{\beta>0} > w^{b*}\Big|_{\beta=0}$;

$$p^{b*}\Big|_{\beta>0} - p^{b*}\Big|_{\beta=0} = \frac{\beta\tau_0 r_0(1-\lambda)\left\{\begin{array}{l}\eta^2(1+\lambda r_0)(1+\lambda\varphi r_0)\left(ak-c\eta^2\right)- \\ 2c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]-c\theta k\eta^2\beta\tau_0 r_0(1-\lambda)\end{array}\right\}}{2(1+\lambda\varphi r_0)(1+\lambda r_0)[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)][2k\theta(1+r_0)-\eta^2(1+\lambda r_0)]}.$$

Thus, when $0 < a \le \frac{2c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]+c\theta k\eta^2\beta\tau_0 r_0(1-\lambda)+c\eta^4(1+\lambda r_0)(1+\lambda\varphi r_0)}{\eta^2 k(1+\lambda r_0)(1+\lambda\varphi r_0)}$,

$p^{b*}\Big|_{\beta>0} \le p^{b*}\Big|_{\beta=0}$; otherwise, when

$a > \frac{2c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]+c\theta k\eta^2\beta\tau_0 r_0(1-\lambda)+c\eta^4(1+\lambda r_0)(1+\lambda\varphi r_0)}{\eta^2 k(1+\lambda r_0)(1+\lambda\varphi r_0)}$, $p^{b*}\Big|_{\beta>0} > p^{b*}\Big|_{\beta=0}$.

Thus, when

$0 < a \le \frac{2c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]+c\theta k\eta^2\beta\tau_0 r_0(1-\lambda)+c\eta^4(1+\lambda r_0)(1+\lambda\varphi r_0)}{\eta^2 k(1+\lambda r_0)(1+\lambda\varphi r_0)}$,

$w^{b*}\Big|_{\beta>0} \le w^{b*}\Big|_{\beta=0}$, $p^{b*}\Big|_{\beta>0} \le p^{b*}\Big|_{\beta=0}$;

when

$$\frac{2c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]+c\theta k\eta^2\beta\tau_0 r_0(1-\lambda)+c\eta^4(1+\lambda r_0)(1+\lambda\varphi r_0)}{\eta^2 k(1+\lambda r_0)(1+\lambda\varphi r_0)} < a \le \frac{6c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]+3c\theta k\eta^2\beta\tau_0 r_0(1-\lambda)+2c\eta^4(1+\lambda r_0)(1+\lambda\varphi r_0)}{\eta^2 k(1+\lambda r_0)(1+\lambda\varphi r_0)},$$

$w^{b*}\Big|_{\beta>0} \le w^{b*}\Big|_{\beta=0}$, $p^{b*}\Big|_{\beta>0} > p^{b*}\Big|_{\beta=0}$;

when

$$a > \frac{6c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]+3c\theta k\eta^2\beta\tau_0 r_0(1-\lambda)+2c\eta^4(1+\lambda r_0)(1+\lambda\varphi r_0)}{\eta^2 k(1+\lambda r_0)(1+\lambda\varphi r_0)},$$

$w^{b*}\Big|_{\beta>0} > w^{b*}\Big|_{\beta=0}$, $p^{b*}\Big|_{\beta>0} > p^{b*}\Big|_{\beta=0}$;

Appendix A.5. Proof of Proposition 3

(1) When $\lambda = 0$,

$$\begin{aligned} d^{b*}\Big|_{\beta>0} - d^{b*}\Big|_{\beta=0} &= \frac{k\theta\beta\tau_0 r_0\left\{2kc\theta^2(1+r_0)(1+\varphi r_0)+\eta^2[a-c\theta(2+2r_0-\beta\tau_0 r_0)]\right\}}{2[2k\theta(1+\varphi r_0)-\eta^2][2k\theta(1+r_0)-\eta^2]} \\ &= \frac{k\theta\beta\tau_0 r_0\left\{c\theta(1+\varphi r_0)\left[2k\theta(1+r_0)-\eta^2\right]+\eta^2[a-c\theta(1+r_0)]\right\}}{2[2k\theta(1+\varphi r_0)-\eta^2][2k\theta(1+r_0)-\eta^2]} \end{aligned}, \text{ with}$$

$2k\theta-\eta^2>0$ and $a-c\theta(1+r_0)>0$, we find $d^{b*}\big|_{\beta>0}>d^{b*}\big|_{\beta=0}$.

(2) When $\lambda=0$, with $L=cd+\frac{1}{2}k(\tau_0+\tau)^2-B>0$, we find $B<B_0$. When $\lambda=0$,

$$\pi_s^{b*}\Big|_{\beta>0}-\pi_s^{b*}\Big|_{\beta=0}=\frac{k\beta\tau_0 r_0\left\{\begin{array}{l}\theta c(1+r_0)[2a-\theta c(2+2r-\beta\tau_0 r_0)][2k\theta(1+\varphi r_0)-\eta^2]\\+\eta^2[a-\theta c(1+\varphi r_0)]^2\end{array}\right\}}{8[2k\theta(1+\varphi r_0)-\eta^2][2k\theta(1+r_0)-\eta^2]}-B\beta\tau_0 r_0.$$

Let $\pi_s^{b*}\big|_{\beta>0}-\pi_s^{b*}\big|_{\beta=0}=0$, we can find $B=B_1$.

Thus, if $B_0<B_1$, when $0\le B<B_0$, $\pi_s^{b*}\big|_{\beta>0}>\pi_s^{b*}\big|_{\beta=0}$. If $B_0>B_1$, when $0\le B<B_1$, $\pi_s^{b*}\big|_{\beta>0}>\pi_s^{b*}\big|_{\beta=0}$; when $B_1\le B<B_0$, $\pi_s^{b*}\big|_{\beta>0}\le\pi_s^{b*}\big|_{\beta=0}$, where

$B_0=\frac{k[a-\theta c(1+\varphi r_0)]\{8kc\theta^2(1+\varphi r_0)^2+\eta^2[a-5\theta c(1+\varphi r_0)]\}}{8[2k\theta(1+\varphi r_0)-\eta^2]^2}$,

$B_1=\frac{k\{\theta c(1+r_0)[2a-\theta c(2+2r-\beta\tau_0 r_0)][2k\theta(1+\varphi r_0)-\eta^2]+\eta^2[a-\theta c(1+\varphi r_0)]^2\}}{8[2k\theta(1+\varphi r_0)-\eta^2][2k\theta(1+r_0)-\eta^2]}$.

(3) When $\lambda=0$,

$$\pi_r^{b*}\Big|_{\beta>0}-\pi_r^{b*}\Big|_{\beta=0}=\frac{k\beta\tau_0 r_0\left\{\begin{array}{l}c\theta^2(1+r_0)(1+\varphi r_0)[2k[2a-c\theta(2+r_0+\varphi r_0)]-c\eta^2]\\+\eta^2[a-c\theta(2+r_0+\varphi r_0)]^2\end{array}\right\}}{4[2k\theta(1+\varphi r_0)-\eta^2][2k\theta(1+r_0)-\eta^2]}.$$

With $a-c\theta(1+r_0)>0$ and $0<\varphi\le1$, we obtain $2a-c\theta(2+r_0+\varphi r_0)=a-c\theta(1+r_0)+a-c\theta(1+\varphi r_0)>0$. Thus, when $0<k<\frac{\eta^2\{c^2\theta^2(1+r_0)(1+\varphi r_0)-[a-c\theta(2+r_0+\varphi r_0)]^2\}}{2c\theta^2(1+r_0)(1+\varphi r_0)[2a-c\theta(2+r_0+\varphi r_0)]}$, $\pi_r^{b*}\big|_{\beta>0}<\pi_r^{b*}\big|_{\beta=0}$; when $k\ge\frac{\eta^2\{c^2\theta^2(1+r_0)(1+\varphi r_0)-[a-c\theta(2+r_0+\varphi r_0)]^2\}}{2c\theta^2(1+r_0)(1+\varphi r_0)[2a-c\theta(2+r_0+\varphi r_0)]}$, $\pi_r^{b*}\big|_{\beta>0}\ge\pi_r^{b*}\big|_{\beta=0}$.

Appendix A.6. Proof of Proposition 4

(1) $\tau^{b*}\big|_{\lambda>0}-\tau^{b*}\big|_{\lambda=0}=\frac{\eta\lambda\theta\varphi r_0(2ak-c\eta^2)(1+\varphi r_0)}{2[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)][2k\theta(1+\varphi r_0)-\eta^2]}>0$,

(2) $\rho^{b*}\big|_{\lambda>0}-\rho^{b*}\big|_{\lambda=0}=\frac{\lambda c\varphi r_0(1+\varphi r_0)}{2(1+\lambda\varphi r_0)}>0$.

(3) $w^{b*}\Big|_{\lambda>0}-w^{b*}\Big|_{\lambda=0}=\frac{\lambda\varphi r_0(1+\varphi r_0)\left\{\begin{array}{l}k\eta^2[a(1+\lambda\varphi r_0)+3c\theta(1+\varphi r_0)(2+\lambda\varphi r_0)]\\-6ck^2\theta^2(1+\varphi r_0)^2-2c\eta^4(1+\lambda\varphi r_0)\end{array}\right\}}{2(1+\lambda\varphi r_0)[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)][2k\theta(1+\varphi r_0)-\eta^2]}$. Thus, when $a>\frac{6ck^2\theta^2(1+\varphi r_0)^2+2c\eta^4(1+\lambda\varphi r_0)-3c\theta k\eta^2(1+\varphi r_0)(2+\lambda\varphi r_0)}{k\eta^2(1+\lambda\varphi r_0)}$, $w^{b*}\big|_{\lambda>0}>w^{b*}\big|_{\lambda=0}$; otherwise, $w^{b*}\big|_{\lambda>0}\le w^{b*}\big|_{\lambda=0}$.

$$p^{b*}\Big|_{\lambda>0}-p^{b*}\Big|_{\lambda=0}=\frac{\lambda\varphi r_0(1+\varphi r_0)\left\{\begin{array}{l}k\eta^2[a(1+\lambda\varphi r_0)+3c\theta(1+\varphi r_0)(2+\lambda\varphi r_0)]\\-6ck^2\theta^2(1+\varphi r_0)^2-2c\eta^4(1+\lambda\varphi r_0)\end{array}\right\}}{2(1+\lambda\varphi r_0)[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)][2k\theta(1+\varphi r_0)-\eta^2]}+\frac{\lambda c\varphi r_0(1+\varphi r_0)}{2(1+\lambda\varphi r_0)}.$$

Thus, when $a>\frac{2ck^2\theta^2(1+\varphi r_0)^2+c\eta^4(1+\lambda\varphi r_0)-c\theta k\eta^2(1+\varphi r_0)(2+\lambda\varphi r_0)}{k\eta^2(1+\lambda\varphi r_0)}$, $p^{b*}\big|_{\lambda>0}>p^{b*}\big|_{\lambda=0}$; otherwise, $p^{b*}\big|_{\lambda>0}\le p^{b*}\big|_{\lambda=0}$.

$$\frac{6ck^2\theta^2(1+\varphi r_0)^2+2c\eta^4(1+\lambda\varphi r_0)-3c\theta k\eta^2(1+\varphi r_0)(2+\lambda\varphi r_0)}{k\eta^2(1+\lambda\varphi r_0)}$$
$$-\frac{2ck^2\theta^2(1+\varphi r_0)^2+c\eta^4(1+\lambda\varphi r_0)-c\theta k\eta^2(1+\varphi r_0)(2+\lambda\varphi r_0)}{k\eta^2(1+\lambda\varphi r_0)}$$
$$=\frac{4ck^2\theta^2(1+\varphi r_0)^2+c\eta^4(1+\lambda\varphi r_0)-2c\theta k\eta^2(1+\varphi r_0)(2+\lambda\varphi r_0)}{k\eta^2(1+\lambda\varphi r_0)}.$$
$$=\frac{c\left[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]\left[2k\theta(1+\varphi r_0)-\eta^2\right]}{k\eta^2(1+\lambda\varphi r_0)}>0$$

when $0<a\le a_3, w^{b*}\big|_{\lambda>0}\le w^{b*}\big|_{\lambda=0}$, $p^{b*}\big|_{\lambda>0}\le p^{b*}\big|_{\lambda=0}$; when $a_3<a\le a_4$, $w^{b*}\big|_{\lambda>0}\le w^{b*}\big|_{\lambda=0}$, $p^{b*}\big|_{\lambda>0}>p^{b*}\big|_{\lambda=0}$; when $a>a_4$, $w^{b*}\big|_{\lambda>0}>w^{b*}\big|_{\lambda=0}$, $p^{b*}\big|_{\lambda>0}>p^{b*}\big|_{\lambda=0}$;

where $a_3=\frac{2ck^2\theta^2(1+\varphi r_0)^2+c\eta^4(1+\lambda\varphi r_0)-c\theta k\eta^2(1+\varphi r_0)(2+\lambda\varphi r_0)}{k\eta^2(1+\lambda\varphi r_0)}$,

$$a_4=\frac{6ck^2\theta^2(1+\varphi r_0)^2+2c\eta^4(1+\lambda\varphi r_0)-3c\theta k\eta^2(1+\varphi r_0)(2+\lambda\varphi r_0)}{k\eta^2(1+\lambda\varphi r_0)}.$$

Appendix A.7. Proof of Proposition 5

(1) When $\beta=0$,

$$d^{b*}\big|_{\lambda>0}-d^{b*}\big|_{\lambda=0}=\frac{k\theta\lambda r_0(1+r_0)\left\{c\theta(1+r_0)\left[2k\theta(1+r_0)-\eta^2\right]+\eta^2(1+\lambda r_0)[a-c\theta(1+r_0)]\right\}}{2(1+\lambda r_0)[2k\theta(1+r_0)-\eta^2(1+\lambda r_0)][2k\theta(1+r_0)-\eta^2]},$$

with $2k\theta-\eta^2>0$ and $a-c\theta(1+r_0)>0$, we can find $d^{b*}\big|_{\lambda>0}>d^{b*}\big|_{\lambda=0}$.

(2) When $\beta=0$,

$$\pi_s^{b*}\big|_{\lambda>0}-\pi_s^{b*}\big|_{\lambda=0}=\frac{k\lambda r_0\theta(1+r_0)^2\left\{2a(1+\lambda r_0)\left(ak-c\eta^2\right)-c^2\theta(1+r_0)\left[2k\theta(1+r_0)-\eta^2(2+\lambda r_0)\right]\right\}}{8(1+\lambda r_0)[2k\theta(1+r_0)-\eta^2(1+\lambda r_0)][2k\theta(1+r_0)-\eta^2]}.$$

Thus, when $0<k\le\frac{\eta^2c[2a(1+\lambda r_0)-c\theta(1+r_0)(2+\lambda r_0)]}{2\left[a^2(1+\lambda r_0)-c^2\theta^2(1+r_0)^2\right]}$, $\pi_s^{b*}\big|_{\lambda>0}\le\pi_s^{b*}\big|_{\lambda=0}$. When $k>\frac{\eta^2c[2a(1+\lambda r_0)-c\theta(1+r_0)(2+\lambda r_0)]}{2\left[a^2(1+\lambda r_0)-c^2\theta^2(1+r_0)^2\right]}$, $\pi_s^{b*}\big|_{\lambda>0}>\pi_s^{b*}\big|_{\lambda=0}$.

(3) When $\beta=0$,

$$\pi_r^{b*}\big|_{\lambda>0}-\pi_r^{b*}\big|_{\lambda=0}=\frac{k\lambda r_0(1+r_0)\left\{\begin{array}{c}\eta^2(1+\lambda r_0)\left[a^2(1+\lambda r_0)-c^2\theta^2(1+r_0)^2\right]+\\ c\theta(1+r_0)\left[\begin{array}{c}2k\theta(1+r_0)\\-\eta^2(2+\lambda r_0)\end{array}\right]\left[\begin{array}{c}2a(1+\lambda r_0)\\-c\theta(1+r_0)(2+\lambda r_0)\end{array}\right]\end{array}\right\}}{4(1+\lambda r_0)^2[2k\theta(1+r_0)-\eta^2(1+\lambda r_0)][2k\theta(1+r_0)-\eta^2]}.$$

With $a-c\theta(1+r_0)>0$, we can find $a(2+2\lambda r_0)-c\theta(1+r_0)(2+\lambda r_0)>0$. Thus, $2a(1+\lambda r_0)-c\theta(1+r_0)(2+\lambda r_0)$.

Thus, when $0<k\le\frac{\eta^2(2+\lambda r_0)}{2\theta(1+r_0)}-\frac{\eta^2(1+\lambda r_0)\left[a^2(1+\lambda r_0)-c^2\theta^2(1+r_0)^2\right]}{2c\theta^2(1+r_0)^2[2a(1+\lambda r_0)-c\theta(1+r_0)(2+\lambda r_0)]}$, $\pi_r^{b*}\big|_{\lambda>0}\le\pi_r^{b*}\big|_{\lambda=0}$. When

$$k>\frac{\eta^2(2+\lambda r_0)}{2\theta(1+r_0)}-\frac{\eta^2(1+\lambda r_0)\left[a^2(1+\lambda r_0)-c^2\theta^2(1+r_0)^2\right]}{2c\theta^2(1+r_0)^2[2a(1+\lambda r_0)-c\theta(1+r_0)(2+\lambda r_0)]},\ \pi_r^{b*}\big|_{\lambda>0}>\pi_r^{b*}\big|_{\lambda=0}.$$

Appendix A.8. Proof of Lemma 3

According to the solution of Stackelberg game equilibrium, we first solve the supplier's response: $\frac{\partial^2\pi_s^c}{\partial(w^c)^2}=-2\alpha\theta(1+\lambda\varphi r_0)<0$, $\frac{\partial^2\pi_s^c}{\partial w^c\partial\tau^c}=\frac{\partial^2\pi_s^c}{\partial\tau^c\partial w^c}=\alpha\eta(1+\lambda\varphi r_0)$, $\frac{\partial^2\pi_s^c}{\partial(\tau^c)^2}=-k(1+\varphi r_0)<0$. Let H be a Hessian of π_s^c. Then $H=\left[\begin{array}{cc}-2\alpha\theta(1+\lambda\varphi r_0) & \alpha\eta(1+\lambda\varphi r_0)\\ \alpha\eta(1+\lambda\varphi r_0) & -k(1+\varphi r_0)\end{array}\right]$.

H is a negative definite because $H_{11} < 0$. With the assumption that $2k\theta - \eta^2 > 0$, $0 \le \lambda < 1$ and $0 < \alpha < 1$, we can obtain $\det(H) = \alpha(1+\lambda\varphi r_0)\left[2\theta k(1+\varphi r_0) - \alpha\eta^2(1+\lambda\varphi r_0)\right] > 0$. Hence, π_s^c is concave in w^c and τ^c. Let $\partial\pi_s^c/\partial w^c = 0$ and $\partial\pi_s^c/\partial\tau^c = 0$, then we find

$$w^c = \frac{k(1+\varphi r_0)[\alpha(a-\theta\rho)(1+\lambda\varphi r_0)+c\theta(1+\varphi r_0)]-\alpha\eta^2 c(1+\varphi r_0)(1+\lambda\varphi r_0)}{\alpha(1+\lambda\varphi r_0)[2k\theta(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]},$$

$\tau^c = \frac{\alpha\eta(a-\theta\rho+\eta\tau_0)(1+\lambda\varphi r_0)-\theta(2k\tau_0+\eta c)(1+\varphi r_0)}{2k\theta(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)}$. Then we solve the retailer's best response. With $\frac{\partial^2\pi_r^c}{\partial(\rho^c)^2} = -\frac{k\theta(1+\varphi r_0)}{2k\theta(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)} < 0$, we can conclude that π_r^c is strictly concave in ρ^c. Let $\partial\pi_r^c/\partial\rho^c = 0$, then we can determine $\rho^{c*} = \frac{a\alpha^2(1+\lambda\varphi r_0)\left[2k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right] - c\theta(1+\varphi r_0)\left[2k\theta(1+\varphi r_0)-\alpha\eta^2(2-\alpha)(1+\lambda\varphi r_0)\right]}{2\alpha\theta(1+\lambda\varphi r_0)[k\theta(1+\alpha)(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]}$.

Thus, we can conclude

$$w^{c*} = \frac{k(1+\varphi r_0)[a\alpha(1+\lambda\varphi r_0)+c\theta(2+\alpha)(1+\varphi r_0)]-2\alpha\eta^2 c(1+\varphi r_0)(1+\lambda\varphi r_0)}{2\alpha(1+\lambda\varphi r_0)[k\theta(1+\alpha)(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]},$$

$$\tau^{c*} = \frac{\alpha\eta(a+2\eta\tau_0)(1+\lambda\varphi r_0)-\theta[2k\tau_0(1+\alpha)+\alpha\eta c](1+\varphi r_0)}{2[k\theta(1+\alpha)(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]},$$

$$d^{c*} = \frac{\theta k(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]}{2(1+\lambda\varphi r_0)[k\theta(1+\alpha)(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]},$$

$$\pi_s^{c*} = \frac{k\alpha(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]^2\left[2k\theta(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)\right]}{8(1+\lambda\varphi r_0)[k\theta(1+\alpha)[1+\varphi r_0]-\alpha\eta^2[1+\lambda\varphi r_0]]^2} + B\varphi r_0,$$

$$\pi_r^{c*} = \frac{k(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]^2}{4(1+\lambda\varphi r_0)^2[k\theta(1+\alpha)(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]}.$$

Appendix A.9. Proof of Corollary 1

$$\frac{\partial\tau^{c*}}{\partial\alpha} = \frac{\eta k\theta(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]}{2[k\theta(1+\alpha)(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]^2}.$$

With $a - c\theta(1+r_0) > 0$, we can find $c\theta(1+\varphi r_0) < c\theta(1+r_0) < a < a(1+\lambda\varphi r_0)$. Thus, $a(1+\lambda\varphi r_0) - c\theta(1+\varphi r_0) > 0$. Consequently, $\frac{\partial\tau^{c*}}{\partial\alpha} > 0$.

$$\frac{\partial d^{c*}}{\partial\alpha} = -\frac{k\theta(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]}{2(1+\lambda\varphi r_0)[k\theta(1+\alpha)(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]^2} < 0;$$

$$\frac{\partial\pi_s^{c*}}{\partial\alpha} = \frac{k^3\theta^2(1+\varphi r_0)^3[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]^2(1-\alpha)}{4(1+\lambda\varphi r_0)[k\theta(1+\alpha)(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]^3} > 0;$$

$$\frac{\partial\pi_r^{c*}}{\partial\alpha} = -\frac{k(1+\varphi r_0)[a(1+\lambda\varphi r_0)-c\theta(1+\varphi r_0)]^2\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]}{8(1+\lambda\varphi r_0)^2[k\theta(1+\alpha)(1+\varphi r_0)-\alpha\eta^2(1+\lambda\varphi r_0)]^2} < 0.$$

Appendix A.10. Threshold Values

$$a_1 = \frac{2c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right]+c\theta k\eta^2\beta\tau_0 r_0(1-\lambda)+c\eta^4(1+\lambda r_0)(1+\lambda\varphi r_0)}{\eta^2 k(1+\lambda r_0)(1+\lambda\varphi r_0)};$$

$$a_2 = \frac{6c\theta k(1+r_0)\left[k\theta(1+\varphi r_0)-\eta^2(1+\lambda\varphi r_0)\right] + 3c\theta k\eta^2\beta\tau_0 r_0(1-\lambda) + 2c\eta^4(1+\lambda r_0)(1+\lambda\varphi r_0)}{\eta^2 k(1+\lambda r_0)(1+\lambda\varphi r_0)}.$$

$$a_3 = \frac{2ck^2\theta^2(1+\varphi r_0)^2+c\eta^4(1+\lambda\varphi r_0)-c\theta k\eta^2(1+\varphi r_0)(2+\lambda\varphi r_0)}{k\eta^2(1+\lambda\varphi r_0)},$$

$$a_4 = \frac{6ck^2\theta^2(1+\varphi r_0)^2+2c\eta^4(1+\lambda\varphi r_0)-3c\theta k\eta^2(1+\varphi r_0)(2+\lambda\varphi r_0)}{k\eta^2(1+\lambda\varphi r_0)}.$$

$$B_0 = \frac{k[a-\theta c(1+\varphi r_0)]\left\{8kc\theta^2(1+\varphi r_0)^2+\eta^2[a-5\theta c(1+\varphi r_0)]\right\}}{8[2k\theta(1+\varphi r_0)-\eta^2]^2};$$

$$B_1 = \frac{k\left\{\theta c(1+r_0)[2a-\theta c(2+2r-\beta\tau_0 r_0)]\left[2k\theta(1+\varphi r_0)-\eta^2\right]+\eta^2[a-\theta c(1+\varphi r_0)]^2\right\}}{8[2k\theta(1+\varphi r_0)-\eta^2][2k\theta(1+r_0)-\eta^2]}.$$

$$k_1 = \frac{\eta^2\left\{c^2\theta^2(1+r_0)(1+\varphi r_0)-[a-c\theta(2+r_0+\varphi r_0)]^2\right\}}{2c\theta^2(1+r_0)(1+\varphi r_0)[2a-c\theta(2+r_0+\varphi r_0)]},$$

$$k_2 = \frac{\eta^2 c[2a(1+\lambda r_0)-c\theta(1+r_0)(2+\lambda r_0)]}{2\left[a^2(1+\lambda r_0)-c^2\theta^2(1+r_0)^2\right]},$$

$$k_3 = \frac{\begin{array}{c}\eta^2 c\theta(2+\lambda r_0)(1+r_0)[2a(1+\lambda r_0)-c\theta(1+r_0)(2+\lambda r_0)] \\ -\eta^2(1+\lambda r_0)\left[a^2(1+\lambda r_0)-c^2\theta^2(1+r_0)^2\right]\end{array}}{2c\theta^2(1+r_0)^2[2a(1+\lambda r_0)-c\theta(1+r_0)(2+\lambda r_0)]}.$$

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