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Cooperation Modes of Operations and Financing in a Low-Carbon Supply Chain

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Abstract: With the significant increase of fossil energy consumption and the ever-worsening pollution of environment, low-carbon development becomes an inevitable choice. Carbon finance can help firms alleviate the finance pressure from carbon emission reduction. This research explores two financing methods, delay-in-payment and bank loan; and two cooperation decisions, carbon emission reduction cooperation and price cooperation. Four scenarios are considered: non-cooperation, partial-cooperation delay-in-payment, supply chain carbon finance (SCCF), and full-cooperation. We discuss how firms make their pricing and carbon emission reduction decisions under different cooperative levels and financing methods. For a manufacturer-dominated supply chain, the results show that SCCF will help the small and medium enterprise seek cooperation with the monopoly manufacturer, and improve supply chain's profit compared to green loan. What's more, SCCF pattern can effectively control the total carbon emission. In addition, we extend the model to consider the retailer-dominated case. The results show that SCCF pattern can help increase the emission reduction rate of the whole supply chain. From the perspective of emission reduction efficiency, it is better for the government to promote the SCCF mode in the retailer-dominated supply chain.

Keywords: cap-and-trade; carbon finance; supply chain finance; supply chain cooperation

1. Introduction

Productivity has increased significantly since the second industrial revolution, and with this the consumption of resources keeps on growing. Meanwhile, the emission of greenhouse gases is rising dramatically, which leads to a series of climate changes and becomes a threat to the ecological environment. The Kyoto Protocol (http://unfccc.int/resource/docs/convkp/kpchinese.pdf) (1997) has established three flexible cooperative mechanisms to reduce emissions, which impels greenhouse gas emissions to become trading goods. As the carbon trading market becomes mature, carbon quotas have gradually developed into liquid assets with investment value. The Paris Agreement (https://unfccc.int/resource/docs/2015/cop21/chi/l09c.pdf) (2015) is the third milestones for carbon emissions reduction. It puts forward a target that the increase of global average temperature should fell below 2 °C. As time goes on, carbon policies and carbon reduction will have greater influences on firms' operations.

Though green production and carbon emission reduction have become an inevitable trend, some companies cannot afford the high abatement costs. More and more companies take carbon emission cost into consideration. An investment plan cannot be passed without thinking about carbon emission costs to BP and Shell [1]. Yihua Co. Ltd., which locates in Wuhan city, Hubei province, China, is a top fertilizer producer in China. It got 100 million Yuan from the Export-Import Bank of China in 2015. This is the biggest green loan in China so far (http://www.eximbank.gov.cn/tm/Newlist/index_343_27624.html). This gives us a hint that there is not only costs, but also opportunities with carbon emissions reduction. The derivative of carbon finance can help a company to deal with carbon emissions reduction cost. Through years of development, carbon finance has some mature business models, such as the Chicago Climate Exchange, the European Union's emissions trading system, and so on. Under such circumstances, it is important for entrepreneurs to consider carbon reduction and relevant finance decisions during operation. However, limited capital is a practical problem for many enterprises.

In the traditional supply chain, supply chain finance (SCF) is one of the effective methods to help small and medium enterprises (SMEs) solve capital constraint problems. SCF is a kind of financing mode whereby banks connect core firms with upstream and downstream firms, and provide overall financial products and services. In the 1980s, world-class firms carried out global business outsourcing for cost minimization, which contributes to the appearance of supply chain management. However, due to different strength of the outsourcing firms, capital constraints or high finance costs will hinder outsourcing. SCF is derived from this. Banks have been under pressure since the financial crisis. Demand for credit from SMEs has risen, but increased regulation and scrutiny of balance sheets has diminished lending capacity. SCF can solve those problems by taking the whole supply chain as a credit bundle.

Based on the above discussion, a new finance pattern which combines the advantages of both carbon finance and SCF seems to be a good choice for firms. With the development of low-carbon economy, studying carbon finance from the supply chain perspective will become a new research direction. Thus, we try to combine carbon finance with supply chain finance, aiming to help the enterprises who do not have enough funds to reduce carbon emissions. In this paper, we innovatively put forward a new pattern: supply chain carbon finance (SCCF). This paper tries to formulate the following research questions: (1) Compared to the traditional carbon finance pattern, does the SCCF pattern effectively control the total carbon emissions of the supply chain? (2) Is it profitable for the manufacturer and the retailer to choose the SCCF pattern? To answer these questions, this paper formulates a two-echelon supply chain consisting of one manufacturer and one retailer. This research explores two financing methods, delay-in-payment and bank loan; and two cooperation decisions, carbon emission reduction cooperation and price cooperation. Based on different cooperation modes, four scenarios are developed and analyzed, including non-cooperation, partial-cooperation delay-in-payment, SCCF, and full-cooperation. The issue we focus on is fresh for introducing carbon finance to the supply chain while giving due consideration to firm's capital constraint. The results of the study will help capital-constrained firms optimize their strategies under a low-carbon environment.

The remainder of this paper is organized as follows. Section 2 reviews the literature. In Section 3, we show the basic notations and preliminaries. A manufacturer-dominated supply chain is considered in this section. We then consider the retailer-dominated supply chain in Section 4. Section 5 conducts numerical experiments to provide more insights. Finally, we offer concluding remarks in Section 6. To make the paper readable, all proofs are presented in Appendix A.

2. Literature Review

This research is closely related to four streams of literature: carbon finance, SCF, supply chain cooperation, and cap-and-trade schemes. To highlight our contributions, we only review the literature that is representative and particularly relevant to our research.

2.1. Carbon Finance and Supply Chain Finance

After the enactment of the international climate polices, carbon finance has developed vigorously and become an important method to solve capital constraints. Carbon emissions trading theory originated in the United States, the promotion of this concept is mainly due to Crocker [2] and Montgomery [3]. Crocker [2] studied the property means application in air pollution control, which laid the groundwork for emissions trading. Montgomery [3] put forward the solution of carbon emissions trading, and proved that the pollution problem of regional combination cost-minimization problem.

Park et al. [4] studied how carbon costs affect the supply chain profit and social welfare. They built a model consisting of a central policy maker, retailers, and consumers. Finance has become a crucial agenda in climate change negotiations in recent years [5]. Hu [6] thinks that finance, an important means and approach for the optimization of resource allocation and redistribution of funds, will definitely play a major role in the development of a low-carbon economy in China. Cachon [7] found that carbon emissions can even rise 67% while firm work on minimizing operating costs. Purdon [8] identified conditions under which the Clean Development Mechanism and other carbon finance projects effectively generate genuine, "additional" carbon credits relying on a systematic empirical investigation of afforestation/reforestation and bioenergy carbon finance projects across Tanzania, Uganda, and Moldova. Lee and Zhong [9] proposed a new financing instrument, called hybrid bond, to build renewable energy projects. The Chinese carbon market is up and running, finance-friendly policies are needed to help the world's largest greenhouse-gas emitter to harness market forces for climate change mitigation [10]. It shows that carbon finance is a good method to develop low-carbon economy. Although the backgrounds of the above studies are similar to that in our model, they do not consider firms' capital constraints and decisions from the perspective of the supply chain. We aim to contribute to this stream of literature by considering firms' emission reduction and pricing decisions under capital constraints in a supply chain. In addition, carbon emission reduction cooperation and price cooperation in the supply chain are considered.

As a new research area in supply chain management, SCF emphasizes that cash flow should correspond with information and logistics. However, the classic M–M theorem, proposed by Modigliani and Miller [11], held the opinion that financial decisions are irrelevant to production decisions in the perfect competitive market, so the financial decisions can be separate from operation decisions. Nonetheless, because there is asymmetric information, bankruptcy costs and interest conflict in the real world, the assumption of a perfect competitive market is not reasonable. That gives financial researchers doubts about the classical M–M theory. Xu and Birge [12] used a traditional newsvendor model to analyze production operation and financing decisions of the capital constraint enterprise in the unperfected competitive market. Buzacott and Zhang [13] believed that financial stats have strongly effect on production decisions. Jing et al. [14] found that the availability of trade and bank credit can make different optimal finance choices. Cai et al. [15] evaluated a capital-constrained retailer's optimal order quantity and the creditors' optimal credit limits under bank and trade credits. Similarly, the roles of bank and trade credits in a supply chain are also considered in our paper. However, we aim to investigate the capital-constrained firm's optimal pricing and carbon emission reduction decisions. The model with a capital-constrained manufacturer and the model with a capital-constrained retailer are considered respectively. SCF is a "1 + N" financing pattern to solve financing difficulty of SMEs by regarding all the enterprises within the supply chain as a whole credit [16]. There are two major perspectives when considering the definition of SCF: the "finance oriented" perspective focused on short-term solutions provided by financial institutions, addressing accounts payable and receivable; and the "supply chain oriented" perspective which might not involve a financial institution, and is focused on working capital optimization in terms of accounts payable, receivable, inventories [17]. Wuttke et al. [18] provided an early step in building knowledge about SCF and in particular how firms adopt SCF, why they adopt differently, and what role suppliers play in the adoption process. Wuttke et al. [19] wonder when the best opportunity is for a company to introduce and adopt SCF. They found that that initial payment terms and procurement volume strongly effect it. Silvestro and Lustrato [20] found that banks can apply SCF by enablers of collaboration, information sharing, and information visibility. Yan et al. [21] formulated a bi-level Stackelberg game for the SCF system in which the bank acts as the leader and the manufacturer as the sub leader, and they concluded that the different interest rates and credit lines would affect the supply chain operations. Zhu et al. [22] predicted the credit risk of China's small and medium-sized enterprises for financial institutions in the supply chain financing by applying the logistic regression and artificial neural network and hybrid models. Li et al. [23] set up a Stackelberg game to examine how enterprises make finance decision while there are multi-supply chains.

Although there has been a lot of research on SCF, none of them consider the financing problem under a low-carbon environment. With the development of a low-carbon economy, companies are faced with more complex decision-making problems. Under the pressure of low-carbon regulation, capital constraint problems are especially prominent in many SMEs. Thus, we aim to put SCF and carbon finance into a system and put forward a new pattern, which is defined as the SCCF pattern and has not been presented before.

2.2. Supply Chain Cooperation and Optimization

The literature on supply chain cooperation and optimization has gained much attention among pricing and supply chain management. Huang and Ke [24] considered a pricing competition and cooperation problem in a two-echelon supply chain with one common manufacturer and duopoly retailers. Yin [25] formulated different supplier alliance models to determine wholesale pricing. Based on the newsvendor model, Krishnan and Winter [26] discussed the cooperation problem of the supply chain under a dynamic environment. Lozano et al. [27] showed that, under different cooperation levels, enterprises will work accordingly in order to reduce costs. Bucki and Suchánek [28] focused on the design and optimization of logistics and production. Ma and Lou [29] investigated the complex characteristics caused by the price competition in multichannel household appliance supply chains. They found that a system in a chaotic state will suffer a larger bullwhip effect than a stable system. Almaktoom [30] provided a reliability-based robust design optimization model to an inventory management system.

Many scholars have realized that any effective action to reduce emissions depends on cooperation between supply chain partners. Gao and Zhang [31] considered a manufacturer and a retailer who plan to invest funds to transform existing production processes to reduce carbon emissions. They applied the Nash bargaining game to design supply chain cooperation mechanisms to achieve supply chain coordination and improve the economic benefits as well as the environmental benefits. Du et al. [32] focused on the impact of consumers' preference to low carbon in the emission-concerned supply chain. They explored how to coordinate the players of the supply chain on environmental pressure and profit-seeking. Benjaafar et al. [33] proposed that operational flexibility and collaboration among firms within the same supply chain could be leveraged to reduce emissions significantly. Zhang and Liu [34] analyzed a revenue sharing mechanism in green supply chain by three-stage non-cooperative game model.

2.3. Cap-and-Trade Scheme

Cap-and-trade can be traced back to Coase theorem which states that if trade in an externality is possible and there are sufficiently low transaction costs, bargaining will lead to a Pareto efficient outcome regardless of the initial allocation of property. Dales [35] applied Coase theorem to water pollution, and raised a mechanism design for emission trading, which is cap-and-trade. A cap-and-trade scheme first defines the legal rights of corporate pollutant emissions, and then allows firms to trade this kind of right freely. This system can control the total amount of pollutant emissions at low cost. The European Union created the EU Emissions Trading Scheme (ETS) in 2005, and set up the European Climate Exchange. EU ETS is the world's first international mandatory emissions trading system covering 27 member countries, uses a cap-and trade scheme. Nowadays, cap-and-trade and carbon tax are the two main low-carbon policies to curb carbon emissions [36]. Many scholars have compared cap-and-trade to carbon tax. Yang et al. [37] investigated the impact of carbon emission trading, carbon tax, and cap-and-trade on channel coordination. Drake et al. [38] looked at how cap-and-trade scheme and carbon tax influence the optimal decision of firm. Carl and Fedor [39] analyzed public revenue generated from global carbon tax and cap-and-trade scheme. They found that carbon taxes generate a range of revenues per capita, but today's cap-and-trade scheme generates only moderate revenues per capita. Some scholars have tried to discern the effect of the cap-and-trade scheme. Du et al. [40] found that the cap-and-trade scheme would constrain the total carbon emissions and promote low-carbon production simultaneously under certain conditions. Yang et al. [41] put forward a new policy which combined carbon quota and carbon tax mechanism and study the misreporting behaviors under three different polices.

There are three points of difference between our work and these related studies. First, carbon finance has not been studied from a micro perspective. Second, the SCCF pattern is not considered in the above studies. The abovementioned literatures show that carbon finance and SCF are useful tools to solve capital constraints and coordinate the supply chain. As carbon finance and SCF have been gradually accepted because of their efficiency, it is an attempt to investigate their combination. Third, capital constraints are not involved in these studies. The existing literature on firms' operational decisions under low-carbon environment mainly contain research on pricing, production, and inventory decisions. This paper is dedicated to solve the optimal financing and carbon emissions reduction decisions with capital constraint under different supply chain cooperation level.

Our contributions in this article are innovative in the following aspects. First, we develop a SCCF pattern. In this pattern, the manufacturer cooperates with other firms to establish a carbon fund. All carbon emission reduction decisions are made by the carbon fund. The carbon fund will get a green loan by mortgaging with carbon quotas and the whole supply chain's credit. Second, we make a comparison between the traditional carbon finance pattern and SCCF pattern. The result shows that SCCF pattern creates slightly higher supply chain profit and obviously higher total carbon reduction emissions. Besides, it can help SMEs get loans. Third, this paper compares the SCCF pattern to delays in payment which are a common trade credit. It turns out that delay-in-payment can earn more profit for supply chains in most situations besides in capital intensive industries. Finally, we provide several sensitive analyses of parameters upon profits and decision-making. In small market and high production cost situations, high cooperation has little effect on supply chain profits, in the meanwhile, the SCCF pattern's effect on carbon emission reduction is similar to delay-in-payment.

3. Models

3.1. Basic Notations and Preliminaries

Consider a two-echelon supply chain which is composed of one manufacture and one retailer. According to firms' different bargaining power, we first consider a manufacturer-dominated supply chain, where the manufacturer is a big enterprise and has sufficient funds to support its carbon emissions reduction behaviors. It produces one kind of product and then sells it to the retailer at a wholesale price. The retailer is defined as a small and medium enterprise. It sells the product to consumers at a retail price. Thus, we only consider the capital constraint of the retailer. A summary of the model notation is included in Table 1, where the subscripts $i = M, R, SC$ are standard for the manufacturer, retailer, and supply chain respectively. We separate the model into four situations according to the cooperative levels and the financing methods.

Table 1. Notations for parameters and variables.

Model Parameters	
a	Market scale
b	Price sensitivity
c	The unit production cost without including reduction cost
D	Delay-in-payment
e_i	Initial carbon emission of unit product, $i = M, R, SC$
F	Carbon finance
G_i	Carbon quota, $i = M, R, SC$
L	Loan amounts of retailer
m	Carbon reduction cost coefficient

Table 1. *Cont.*

Model Parameters	
N	Initial capital
p_c	Carbon price, external variable
Q	Production quantity
r	Interest rate, external variable
T_i	Volume of emission trade, $i = M, R, SC$
$C(\Gamma_i)$	Cost of carbon reduction, $i = M, R, SC$
$E_i(Q)$	The actual emission,$i = M, R, SC$
NC	Non-cooperation
PC	Partial-cooperation
FC	Full-cooperation
Decision variables	
p	Retail price
w	Wholesale price
Γ_i	The reduction rate of greenhouse gases, $\Gamma_i \in (0, 1)$

In this paper, four different scenarios are considered: non-cooperation (NCF), supply chain carbon finance (SCCF), partial-cooperation delay-in-payment (PCD), and full cooperation (FC). In practice, delay-in-payment is a common trade credit and is widely used by supply chain members. Price cooperation is also considered by practitioners and researchers. In a low-carbon environment, green loans provide opportunities for SMEs to gain more funds to deal with carbon emissions reduction costs. In addition, carbon emissions reduction decisions have become a focal point for the sustainable development of enterprises. Thus, it is necessary to analyze some new cooperation patterns under a low-carbon environment. Based on the previous literature and the above analysis, in this paper we analyze four situations to simulate the supply chain in two dimensions: financing method and cooperative level. It is summarized in Table 2.

Table 2. Summarization of four situations.

Patterns	**Finance**		**Cooperation**	
	Delay-in-payment	**Bank Loan**	**Reduction**	**Price**
NCF	×	√	×	×
PCD	√	×	√	×
SCCF	×	√	√	×
FC	√	×	√	√

We assume that the abatement cost is a one-time investment—such as buying new production equipment—and the reduction cost is not relevant to the production quantity. However, it will be influenced by some features of firms, such as technical level, the consciousness of manager, and so on. In this paper, we use the quadratic function to describe the cost pattern, which is widely adopted in the previous literature [42,43]. Thus, the emission reductions cost is $C(\Gamma_i) = \frac{1}{2}m\Gamma_i^2$, where Γ_i is the reduction rate of greenhouse gases and m represents the carbon reduction cost coefficient. The larger m is, the higher carbon reduction cost the firm has under the same carbon emission reduction rate. The manufacturer and the retailer are restricted to total carbon emissions in a cap-and-trade scheme. Both of them are emitting greenhouse gases, and the actual emissions after using low-carbon technologies are $E_i(Q) = (1 - \Gamma_i)e_iQ$. They can choose to abide it alone or as a whole. The government will impose significant fines on firms if they emit excess greenhouse gases. Every firm can sell or buy quota in the carbon market. Hence, the quota of carbon emissions is equal to the general emissions plus trading emissions $T_i = G_i - (1 - \Gamma_i)e_iQ$. If $T_i > 0$, it means that the firm sells quotas in carbon market. Otherwise, the firm buys quotas in carbon market. The retailer has capital constraints and cannot support the quantity during profit-maximizing. So, when the retailer chooses to obtain a loan from bank, the loan amount is $L = wQ + \frac{1}{2}m\Gamma_R - N$. In our model, we capture the cost of capital chiefly through the parameter r, which is understood as the interest rate. The demand of production is negatively relative with price. Without loss of generality, we assume that $Q = a - bp$, where a is market scale and b is price sensitivity. For ease of discussion, the supply chain's emission reduction is denoted as $\Gamma_{SC} = (e_R\Gamma_R + e_M\Gamma_M)/(e_R + e_M)$.

We consider a single-period product market, where the manufacturing is monopolized by one firm. The manufacturer is the core firm in this supply chain. The retailer in this supply chain is a SME. The retailer does not have enough funds to reduce its carbon emissions. We assume that the government uses a cap-and-trade scheme to restrict firms' carbon emissions. This means that the government allocates initial carbon quotas for each firm and allows them to trade their quotas in the carbon market. After trading in the carbon market, every firm's emissions should not exceed their quotas (including the initial one and purchased one). Otherwise, the firm will suffer strict punishment from the government. We discuss how firms make their pricing and carbon emissions reduction decisions under different cooperative levels and financing methods. We derive the equilibrium solutions for the supply chain members in four situations: NCF, SCCF, PCD, and FC. The sequence of events in the manufacturer-dominated supply chain is shown in Figure 1. Two firms decide carbon emission reduction rate in first stage. If they do not cooperate in this stage (NCF), there is a Nash game which means that they decide carbon emissions reduction rates simultaneously. In SCCF, PCD, and FC situations, they decide carbon emission reduction rate together. In the second stage, two firms make the pricing decisions. In FC, they decide the retail price together. In NCF, SCCF, and PCD patterns, the manufacturer decides the wholesale price as a Stackelberg leader and retailer decides the retail price as follower.

The two firms carry out cooperation of reduction emission in the first stage, but they still make their pricing decision independently. The target in the first stage is maximizing the profit of the supply chain, and the target in the second stage is maximizing the profit of the firm.

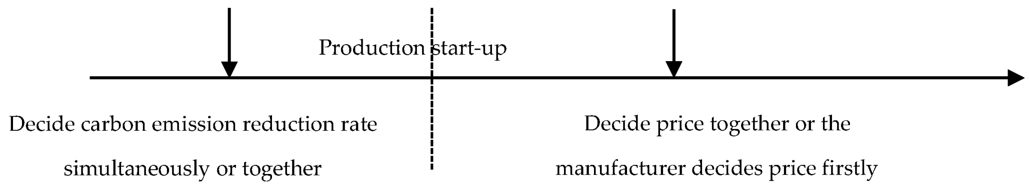

Figure 1. Sequence of events in a manufacturer-dominated supply chain.

To provide a foundation of cooperation, we make an assumption that two firms can exchange their quotas by negotiation. Therefore, the supply chain can reduce carbon emissions as a unit. Firms can save carbon emission cost by allocating quotas effectively. Thus, if the retailer has a low carbon emissions cost, he can transfer some quotas to the manufacturer. The retailer can share its quotas with the manufacturer; in return, the manufacturer provides financial cooperation. The total carbon quotas may lead to cost or profit depending on the initial quotas and actual carbon emissions. At the end of the selling season, both firms allocate the total cost and profit where the negotiation is involved.

Several patterns are studied according to different cooperative levels and financing methods. Both firms can choose whether or not to cooperate in carbon emission reduction and price decisions, and the retailer can choose the financing methods. In this paper, we use a two-echelon model consisting of one manufacturer and one capital constraint retailer to demonstrate these situations.

3.2. Non-Cooperation with Finance Pattern (NCF)

Under situation NCF, both firms decide their carbon emission reduction rate independently, but the retailer loans from the bank by itself. After acquiring the wholesale price, the retailer borrows money and decides his retail price (See Figure 2).

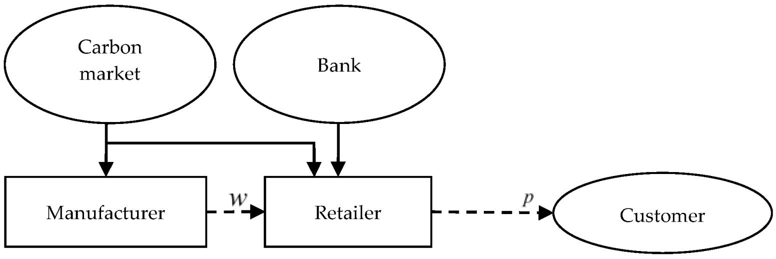

Figure 2. Non-cooperation with finance pattern (NCF).

In this non-cooperation situation, the retailer solves the capital problem by applying to bank for green loan and bear the full loan cost. Thus, the loan amount, the retailer's profit, and the manufacturer's profit are as follows

$$\begin{cases} L = wQ + \frac{1}{2}m\Gamma_R^2 - N \\ \Pi_R^{NCF} = (p-w)Q - \frac{1}{2}m\Gamma_R^2 + T_R p_c - Lr \\ \Pi_M^{NCF} = (w-c)Q - \frac{1}{2}m\Gamma_M^2 + T_M p_c \end{cases}.$$

Lemma 1. *When the supply chain chooses a loan method to deal with the capital constraints, the optimal pricing and reduction decisions in the situation NCF are*

$$\begin{cases} p^{NCF} = \dfrac{\left\{3a + bc(1+r) + bp_c\left[e_R\left(1-\Gamma_R^{NCF}\right) + e_M(1+r)\left(1-\Gamma_M^{NCF}\right)\right]\right\}}{4b} \\ w^{NCF} = \dfrac{\left\{a + bc(1+r) + bp_c\left[-e_R\left(1-\Gamma_R^{NCF}\right) + e_M(1+r)\left(1-\Gamma_M^{NCF}\right)\right]\right\}}{2b(1+r)} \end{cases}$$

and

$$\begin{cases} \Gamma_R^{NCF} = \dfrac{e_R p_c\{a - bc(1+r) - bp_c[e_R + (1+r)e_M]\}}{8(1+r)m - bp_c^2\left[e_R^2 + 2(1+r)^2 e_M^2\right]} \\ \Gamma_M^{NCF} = \dfrac{2e_M p_c(1+\mathrm{r})\{a - bc(1+r) - bp_c[e_R + (1+r)e_M]\}}{8(1+r)m - bp_c^2\left[e_R^2 + 2(1+r)^2 e_M^2\right]} \end{cases}.$$

3.3. *Supply Chain Carbon Finance Pattern (SCCF)*

Under situation SCCF, they have cooperated in carbon emission reduction, which means that they share the carbon emission quotas to each other, allocate the quotas, and decide to buy/sell in carbon market together. The two firms build a carbon fund to allocate the quotas and make a deal in carbon market. First, they decide the carbon emission reduction rate together, and then the manufacturer decides wholesale price. The retailer decides the retail price according to the reduction rate, wholesale price, and interest rate (see Figure 3).

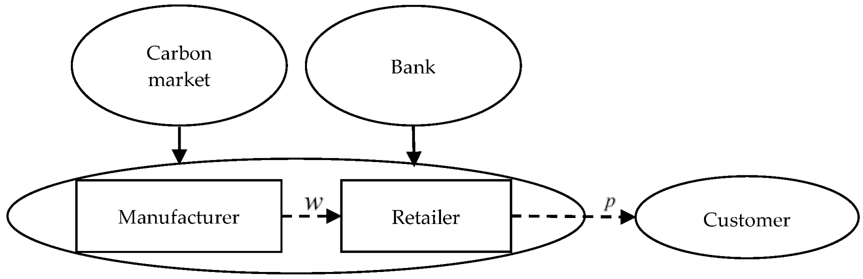

Figure 3. Supply chain carbon finance pattern (SCCF).

Under such a pattern, two firms cooperate in carbon emission reduction. They set up a carbon fund to apply to the bank for a green loan. Essentially, a green loan is one kind of bank loan, but it takes the carbon emission reduction policy into account and supports firms in reducing carbon emissions through financing. A green loan means that the bank allows the firm to provide carbon quotas as collateral. SCCF expands this concept of green loans by allowing supply chain quotas and credit as collateral. Under the cap-and-trade scheme, the government caps total emissions but allows emitters to trade pollution allowances. The integrated supply chain complies with the quotas which is equal to the sum of both firms' quotas. The structure of SCCF is shown in Figure 3. There are three steps for this pattern:

First, the manufacturer in the supply chain plays the leading role in uniting the upstream and downstream firms to establish a carbon fund. Carbon emission reduction rate and carbon quotas trading volume are decided by the fund. The fund mortgages the whole supply chain's carbon quotas and the credit of the supply chain as a loan from bank. This carbon fund is supervised by the whole supply chain and bank.

Second, after the fund gets the green loan from bank, it allocates the green loan and carbon emission reduction tasks to the firms which have the lowest reduction costs, and it trades the carbon quota in carbon market. We assume that carbon trading can be completed instantaneously, and that the demand of firms can always be satisfied. Thus, the volume of carbon trade is only effected by carbon trading price and reduction cost.

Finally, at the end of the selling season, the fund pays off the loan and distributes profits or costs caused by carbon emission reduction.

Compared with the traditional carbon finance pattern, SCCF brings more loans by treating both the firms in the supply chain as a credit bundle. For SMEs, due to a lack of collateral, they are hardly able to get loans by themselves. The core firm usually has good credit. Thus, taking the SCCF pattern, SMEs can get loan as part of the supply chain. By allocating the high carbon reduction rate to the firm with low reduction cost, this pattern uses less money to complete the same reduction target. Carrying out SCCF requires the firms to cooperate more closely, which can strengthen the competitiveness of the supply chain.

In this case, the bank is chosen as the creditor and the retailer must bear all the loan costs. The loan amount and the profit of whole supply chain in the first stage are

$$\begin{cases} L = wQ + \frac{1}{2}m\Gamma_R^2 - N \\ \Pi_{SC}^{SCCF} = (p-c)Q + (T_M + T_R)p_c - \frac{1}{2}m\Gamma_R^2 - \frac{1}{2}m\Gamma_M^2 - Lr \end{cases}.$$

The retailer's profit and the manufacturer's profit in the second stage are

$$\begin{cases} \Pi_R^{SCCF} = (p-w)Q - \frac{1}{2}m\Gamma_R^2 + T_R p_c - Lr \\ \Pi_M^{SCCF} = (w-c)Q - \frac{1}{2}m\Gamma_M^2 + T_M p_c \end{cases}.$$

Lemma 2. *The optimal pricing and reduction decisions in the SCCF situation are*

$$\begin{cases} p^{SCCF} = \dfrac{\{3a + bc(1+r) + be_R p_c(1-\Gamma_R^{SCCF}) + b(1+r)e_M p_c(1-\Gamma_M^{SCCF})\}}{4b} \\ w^{SCCF} = \dfrac{\{a + bc(1+r) - be_R p_c(1-\Gamma_R^{SCCF}) + b(1+r)e_M p_c(1-\Gamma_M^{SCCF})\}}{2b(1+r)} \end{cases}$$

and

$$\begin{cases} \Gamma_R^{SCCF} = \dfrac{e_R p_c(3+\mathrm{r})\{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\}}{8m(1+r)^2 - bp_c^2(3+\mathrm{r})\left[e_R^2 + e_M^2(1+\mathrm{r})^3\right]} \\ \Gamma_M^{SCCF} = \dfrac{(1+r)^2(3+r)e_M p_c\{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\}}{8m(1+r)^2 - bp_c^2(3+\mathrm{r})\left[e_R^2 + e_M^2(1+\mathrm{r})^3\right]} \end{cases}.$$

We can find that the prices are the same in the NCF and SCCF. Although the reduction rates are different, they still have a similar structure. This is because they have the same profit functions in the price-decision stage. However, in the reduction decision stage, the SCCF scenario takes the whole profit of the supply chain into account. Thus, interest rates influence both retailer's and manufacturer's decisions.

3.4. Partial-Cooperation with Delay-in-Payment Pattern (PCD)

Under PCD, the manufacturer allows the retailer to delay-in-payment. So the retailer does not need to take a loan. First, they decide the carbon emission reduction rate together, and then the manufacturer decides wholesale price. The retailer decides the retail price according to the emission reduction rate and wholesale price (see Figure 4).

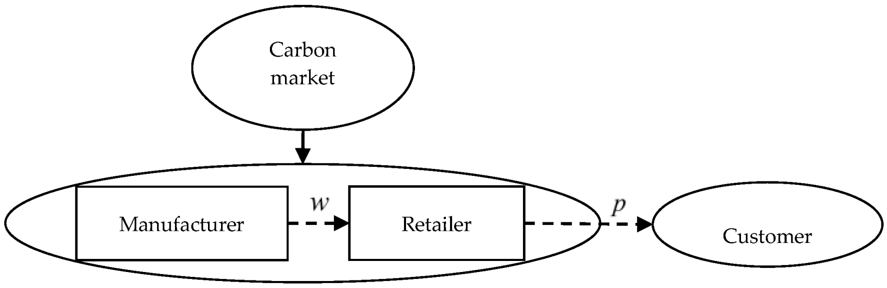

Figure 4. Partial-cooperation with delay-in-payment pattern (PCD).

In this case, the manufacturer is the creditor and helps the retailer to solve his capital constraint. The profit of the whole supply chain in the first stage is

$$\Pi_{SC}^{PCD} = (p-c)Q + (T_M + T_R)p_c - \frac{1}{2}m\Gamma_R^2 - \frac{1}{2}m\Gamma_M^2.$$

The retailer's profit and the manufacturer's profit in the second stage are

$$\begin{cases} \Pi_R^{PCD} = (p-w)Q - \frac{1}{2}m\Gamma_R^2 + T_R p_c \\ \Pi_M^{PCD} = (w-c)Q - \frac{1}{2}m\Gamma_M^2 + T_M p_c \end{cases}.$$

Lemma 3. *When the supply chain chooses the delay-in-payment method, the optimal pricing and reduction decision in the PCD situation are*

$$\begin{cases} p^{PCD} = \dfrac{3a + bc + bp_c[e_R(1-\Gamma_R^{HCD}) + e_M(1-\Gamma_M^{HCD})]}{4b} \\ w^{PCD} = \dfrac{a + bc + bp_c[-e_R(1-\Gamma_R^{NCD}) + e_M(1-\Gamma_M^{HCD})]}{2b} \end{cases}$$

and

$$\begin{cases} \Gamma_R^{PCD} = \dfrac{3e_R p_c[a - bc - bp_c(e_R + e_M)]}{8m - 3bp_c^2(e_R^2 + e_M^2)} \\ \Gamma_M^{PCD} = \dfrac{3e_M p_c[a - bc - bp_c(e_R + e_M)]}{8m - 3bp_c^2(e_R^2 + e_M^2)} \end{cases}.$$

3.5. Full Cooperation Pattern (FC)

Under FC, two firms build a strategic alliance. In the beginning, they decide the reduction rate together—such as investing in emission control devices—and the manufacturer provides product to the retailer without charge. After selling out, they decide to sell/buy quotas in the carbon market and allocate the profit. In this situation, the manufacturer does not charge the retailer wholesale price (see Figure 5).

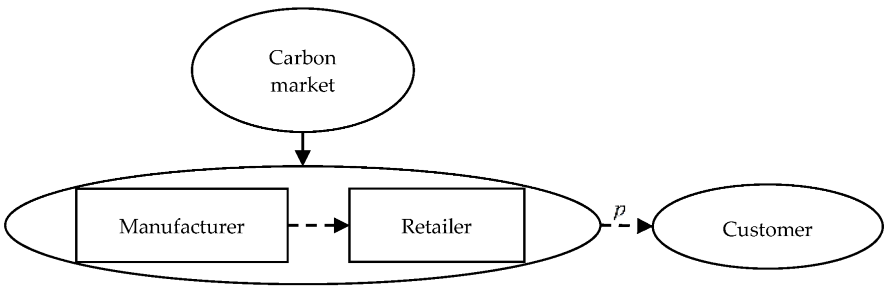

Figure 5. Full cooperation pattern (FC).

In this case, the highest level of cooperation is completely collaborative in carbon emissions reduction and pricing. Two firms set up a coalition and make decisions together, and the manufacturer will allow retailer to delay-in-payment. Thus, the retailer has no loan costs. The profits of whole supply chain are

$$\Pi_{SC}^{FC} = (p - c)Q - \frac{1}{2}m\left(\Gamma_R^2 + \Gamma_M^2\right) + (T_M + T_R)p_c.$$

Lemma 4. *For FC situations, the pricing optimal and reduction decision are*

$$p^{FC} = \frac{a + bc + bp_c[e_M(1-\Gamma_M^{TC}) + e_R(1-\Gamma_R^{TC})]}{2b}$$

and

$$\begin{cases} \Gamma_R^{FC} = \dfrac{e_R p_c[a - bc - bp_c(e_M + e_R)]}{2m - bp_c{}^2(e_M^2 + e_R^2)} \\ \Gamma_M^{FC} = \dfrac{e_M p_c[a - bc - bp_c(e_M + e_R)]}{2m - bp_c{}^2(e_M^2 + e_R^2)} \end{cases}.$$

3.6. Results and Discussion

This section performs analyses and discussions about the optimal decisions. The relationship between some parameters and decision variables and comparison of optimal decisions among different situations are considered.

The pricing decisions rely on carbon emission reduction decisions. The reduction rates are symmetrical in PCD and FC. In addition, the reduction rate is independent of initial capital. The original state of firms and the market have a strong effect on decision making. This may be a result of different bargaining power. Usually, the firm who has more money or core technology will have more bargaining power, and this firm can get a dominant position in the cooperation.

Theorem 1. *In all situations, Γ_R and Γ_M are increasing with a.*

As a product grows in popularity, carbon emissions decrease. There are three reasons to explain this phenomenon. First, it can be explained by economies of scale. Specialization of work effort is necessary to achieve efficiency and productivity. With the increase of production, workers can increase proficiency. Second, firms can effectively undertake research and development costs when they are facing a larger market. Technology development is the key to increase emission reduction rate. Third, a larger market means lots of competitors, firms need to highlight their advantages by product differentiation. Producing a green product may be a fine option since more and more people pay attention to environmental protection.

Theorem 2. *(a) In situation NCF, if $e_R > 2e_M$, $\Gamma_R^{NCF} > \Gamma_M^{NCF}$, and if $e_R \leq 2e_M$,$\Gamma_R^{NCF} \leq \Gamma_M^{NCF}$;*
(b) In situation SCCF, If $e_R > (1+r)^2 e_M$, $\Gamma_R^{SCCF} > \Gamma_M^{SCCF}$, and if $e_R \leq (1+r)^2 e_M$,$\Gamma_R^{SCCF} \leq \Gamma_M^{SCCF}$;
(c) In situation PCD and FC, if $e_R > e_M$, $\Gamma_R^{PCD,FC} > \Gamma_M^{PCD,FC}$, and if $e_R \leq e_M$,$\Gamma_R^{PCD,FC} \leq \Gamma_M^{PCD,FC}$.

The firm who has higher initial emissions will have a higher reduction rate. Diminishing marginal returns can account for such a phenomenon. The firm with higher emissions can usually reduce them through some simply actions, such as improving the employee's green consciousness. However, for firms that are already making efforts to reduce emissions, they must pay a higher price to get a unit of emission reduction. This provides a principle for allocating the reduction responsibility between the firms. When we use external financing methods to solve capital constraints, the value of the reduction rate not only relates to the initial emissions, but also to the interest rate. Allocating the reduction responsibility according to reduction costs can significantly improve profits of the whole supply chain.

Comparing reduction rates between the manufacturer and retailer in NCF and SCCF situations, we can find that the reduction rate of the retailer is lower than that of the manufacturer under the same conditions. In other words, the reduction of the downstream firm is more difficult than the upstream firm. Hence, we should strictly control emissions from upstream. With the same reduction investment, upstream firms can play a greater role.

Unless a retailer has twice the initial carbon emissions of the manufacturer, retailer's reduction rates will not be larger than manufacturers in an NCF situation. In SCCF, the threshold becomes $(1+r)^2$. For PCD and FC, those become 1. Interest rates are ordinarily lower than 40%. Thus $(1+r)^2 < 2$. The threshold decreases with the cooperative level. As the relationship between the two firms becomes intimate, the maximization of supply chain profit becomes a common goal. The reduction of cost comes from decreased reduction rates. The SCCF pattern can improve the manufacturer's reduction situation.

$$\text{Denote } m_1 = \frac{be_m^2 p_c^2 (3+\mathrm{r})(1-r)(1+r)}{16}, m_2 = \frac{be_R^2 e_m^2 p_c^2 r(1-r)(3+r)}{16me_R^2 + 8(1+r)^3 e_m^2}.$$

Theorem 3. *For situations considering carbon finance, SCCF and NCF, the reduction rates satisfy*

(a) For the manufacturer, $\Gamma_M^{SCCF} \geq \Gamma_M^{NCF}$*;*
(b) For the retailer, if $m > m_1$*,* $\Gamma_R^{SCCF} > \Gamma_R^{NCF}$*, and if* $m \leq m_1$*,*$\Gamma_R^{SCCF} \leq \Gamma_R^{NCF}$*;*
(c) For the supply chain, if $m > m_2$*,* $\Gamma_{SC}^{SCCF} > \Gamma_{SC}^{NCF}$*, and if* $m \leq m_2$*,*$\Gamma_{SC}^{SCCF} \leq \Gamma_{SC}^{NCF}$*.*

The manufacturer will undertake more reduction tasks in a SCCF situation. In fact, the manufacturer usually has larger carbon emissions than the retailer. Therefore, carbon emissions reduction is relatively painless for manufacturers. When using the SCCF pattern, carbon funds can allocate a reduction target for supply chain members according to reduction costs. This is an important profit resource of the SCCF pattern.

For the retailer, the reduction rate depends on his carbon reduction cost coefficient. It means that, only when m is large enough ($m_R > m_1$), will the retailer have a higher reduction rate in a SCCF situation compared to a NCF situation. The supply chain's reduction rate presents the same pattern regularity. While $m_{SC} > m_2$, the reduction rate of supply chain in a SCCF situation is larger than that in a NCF situation. For threshold m_1, it just relies on manufacturer's initial carbon emission, carbon trading price, and interest rate. When the manufacturer's initial emissions are much greater than the quotas, retailer in SCCF pattern will take more reduction task for achieving lower reduction costs.

In a SCCF situation, firms cooperate to reduce the carbon emission. It builds up a flexible carbon emission mechanism. Firms can allocate the emission reduction task to the firm which has the low reduction cost. Hence, compared to a NCF situation, supply chains can reduce more carbon emissions with the same conditions. The government should encourage banks to offer more financial services so as to encourage firms to reduce their greenhouse gases emissions. In addition, the government should promote the development of suitable carbon finance pattern.

Theorem 4. *For the situation considering delay-in-payment, PCD and FC, the profit and reduction rate satisfy* $\Pi_{SC}^{PCD} \leq \Pi_{SC}^{FC}$*,* $\Gamma_R^{PCD} \leq \Gamma_R^{FC}$*,* $\Gamma_M^{PCD} \leq \Gamma_M^{FC}$ *and* $\Gamma_{SC}^{PCD} \leq \Gamma_{SC}^{FC}$*.*

When the supply chain takes delay-in-payment method, the capital constraint is solved without extra cost. In that case, the profit and reduction rate of whole supply chain is related to the cooperative level. Calculations indicate that the supply chain's profit in situation FC is larger than that in situation PCD. In other words, the higher cooperative level brings the higher profit. What's more, the reduction rate in full cooperation is higher than that in partial cooperation. Therefore, when the firms decide to choose a delay-in-payment method to deal with the capital constraint, they should eliminate the double marginalization to improve the profit and reduce the carbon emission by increasing cooperative level.

Jing et al. [14] found that the overall supply chain efficiency under trade credit financing is higher than that under bank credit financing when production cost is low. However, our result shows that the trade credit financing cannot effectively increase the supply chain's efficiency under a low-carbon environment. A higher cooperative level is needed to enhance the profit of the supply chain. The FC pattern which combines trade credit and carbon emissions reduction cooperation is proven to be a better mode under low-carbon environment. Although the full cooperation situation has lots of advantages, it is not popular in real life. That is because establishing such an alliance means two firm have a broad and close ties, and this requires a reliable credit evaluation mechanism and long-standing cooperation.

4. Extensions

In this section, we consider the retailer-dominated supply chain. In practice, some large retailers have more bargaining power than manufacturers. For instance, Gome and Suning have thousands of stores. Relying on such a strong channel advantage, Gome plays a powerful position in the pricing game. In order to improve their profit, they will do their best to reduce appliance manufacturers' wholesale price and achieve delay-in-payment. Under such conditions, if the manufacturer also faces the government's low-carbon regulation, funds will be overstretched. In this section, we concentrate on the retailer-dominated case, where the manufacturer has funding constraints. We aim to analyze the impact of ordinary loans, supply chain financing, and carbon finance on firms' operational decisions and profits. The decision sequence is shown in Figure 6. First, the retailer decides the price markup θ, where $p = w + \theta$. After realizing the price markup, the manufacturer decides the sales price p.

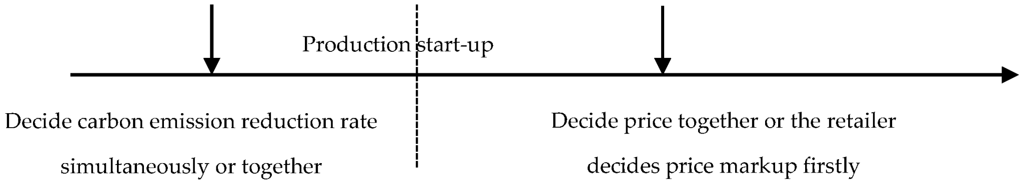

Figure 6. Sequence of events in retailer-dominated supply chain.

4.1. Models

Situation NCF—Under a non-cooperation situation, the manufacturer and the retailer make decisions independently. The manufacturer has capital constraint and the initial capital is denoted by N. The manufacturer loans from bank by itself and the loan amount is $L = cQ + \frac{1}{2}m\Gamma^2{}_M - N$. Thus, the profits of the retailer and the manufacturer are

$$\begin{cases} \widetilde{\Pi}_R^{NCF} = \theta Q - \frac{1}{2}m\Gamma_R^2 + T_R p_c \\ \widetilde{\Pi}_M^{NCF} = (p - \theta - c)Q - \frac{1}{2}m\Gamma_M^2 + T_M p_c - Lr \end{cases}.$$

The optimal decisions are shown in Tables 3 and 4.

Table 3. Optimal pricing decisions in the retailer-dominated case.

Patterns	p	θ
NCF	$\frac{a+b[e_M p_c(1-\Gamma_M)+c(1+r)+\theta]}{2b}$	$\frac{\{a-bc(1+r)+be_R p_c(1-\Gamma_R^{NCF})-be_M p_c(1-\Gamma_M^{NCF})\}}{2b}$
SCCF	$\frac{a+b[e_M p_c(1-\Gamma_M)+c(1+r)+\theta]}{2b}$	$\frac{\{a-bc(1+r)+be_R p_c(1-\Gamma_R^{NCF})-be_M p_c(1-\Gamma_M^{NCF})\}}{2b}$
PCD	$\frac{a+b[\theta+c+e_M p_c(1-\Gamma_M)]}{2b}$	$\frac{\{a-bc-bp_c[-e_R(1-\Gamma_R^{HCD})+e_M(1-\Gamma_M^{HCD})]\}}{2b}$

Table 4. Optimal emission reduction rate in the retailer-dominated case.

Patterns	$\widetilde{\Gamma}_M$	$\widetilde{\Gamma}_R$
NCF	$\frac{e_M p_c[a-bc(1+r)-bp_c(e_R+e_M)]}{8m-bp_c^2(e_R^2+2e_M^2)}$	$\frac{2e_R p_c[a-bc(1+r)-bp_c(e_R+e_M)]}{8m-bp_c^2(e_R^2+2e_M^2)}$
SCCF	$\frac{3e_M p_c[a-bc(1+r)-bp_c(e_R+e_M)]}{8m(1+r)-3bp_c^2[e_R^2+e_M^2(1+\mathrm{r})]}$	$\frac{3(1+r)e_R p_c[a-bc(1+r)-bp_c(e_R+e_M)]}{8m(1+r)-3bp_c^2[e_R^2+e_M^2(1+\mathrm{r})]}$
PCD	$\frac{3e_M p_c[a-bc-bp_c(e_R+e_M)]}{8m-3bp_c^2(e_R^2+e_M^2)}$	$\frac{3e_R p_c[a-bc-bp_c(e_R+e_M)]}{8m-3bp_c^2(e_R^2+e_M^2)}$

Situation SCCF—Under supply chain carbon finance, the manufacturer and the retailer cooperate on carbon emissions reduction. They will set up a carbon fund to jointly apply for loans from banks, so as to solve the manufacturer's funding problem. In this case, the manufacturer should bear the interest costs arising from loans, which is denoted as Lr. Thus, in the first stage of the game, they jointly decide the emission reduction rate with the target of maximizing the whole supply chain's profit. The profit function of the supply chain is

$$\widetilde{\Pi}_{SC}^{SCCF} = (p - c)Q + (T_M + T_R)p_c - \frac{1}{2}m\Gamma_R^2 - \frac{1}{2}m\Gamma_M^2 - Lr.$$

In the second stage, the manufacturer and the retailer decide their price independently. The retailer decides θ, while the manufacturer decides p.

$$\begin{cases} \widetilde{\Pi}_R^{SCCF} = \theta Q - \frac{1}{2} m \Gamma_R^2 + T_R p_c \\ \widetilde{\Pi}_M^{SCCF} = (p - \theta - c) Q - \frac{1}{2} m \Gamma_M^2 + T_M p_c - Lr \end{cases}.$$

Situation PCD—In this case, the manufacturer and the retailer cooperate in emission reduction. The retailer pays before production. Thus, the manufacturer does not need to apply for a loan from the bank. In the first stage of game, the profit function of the supply chain is

$$\widetilde{\Pi}_{SC}^{PCD} = (p - c) Q + (T_M + T_R) p_c - \frac{1}{2} m \Gamma_R^2 - \frac{1}{2} m \Gamma_M^2.$$

In the second stage, the manufacturer and the retailer decide their price independently. The profit functions of the supply chain members are

$$\begin{cases} \widetilde{\Pi}_R^{PCD} = \theta Q - \frac{1}{2} m \Gamma_R^2 + T_R p_c \\ \widetilde{\Pi}_M^{PCD} = (p - \theta - c) Q - \frac{1}{2} m \Gamma_M^2 + T_M p_c \end{cases}.$$

In the full-cooperation case, the manufacturer and the retailer jointly decide the retail price. Therefore, this situation is consistent with the corresponding case in manufacturer-dominated supply chain. Thus, we omit it.

4.2. Results and Discussion

Theorem 5. *(a) In situation NCF, if* $e_M > 2e_R$, $\widetilde{\Gamma}_M^{NCF} > \widetilde{\Gamma}_R^{NCF}$, *and if* $e_M \le 2e_R$,$\widetilde{\Gamma}_M^{NCF} \le \widetilde{\Gamma}_R^{NCF}$;
(b) In situation SCCF, if $e_M > (1+r)e_R$, $\widetilde{\Gamma}_M^{SCCF} > \widetilde{\Gamma}_R^{SCCF}$, *and if* $e_M \le (1+r)e_R$,$\widetilde{\Gamma}_M^{SCCF} \le \widetilde{\Gamma}_R^{SCCF}$;
(c) In situation PCD, if $e_M > e_R$, $\widetilde{\Gamma}_M^{PCD} > \widetilde{\Gamma}_R^{PCD}$, *and if* $e_M \le e_R$,$\widetilde{\Gamma}_M^{PCD} \le \widetilde{\Gamma}_R^{PCD}$.

In the retailer-dominated case, if the manufacturer and the retailer have the same initial carbon emission, the retailer has higher reduction rate. This conclusion is similar to that in the manufacturer-dominated case. In the retailer-dominated case, if $e_M > (1+r)e_R$, then $\widetilde{\Gamma}_M^{SCCF} > \widetilde{\Gamma}_R^{SCCF}$. Under SCCF, the manufacturer and the retailer cooperate in carbon emission reduction. Thus, the result shows that if the manufacturer and the retailer have the same initial carbon emission, then retailer will reduce more carbon emissions. In other words, the retailer as the leader in the supply chain has more emission reduction responsibilities.

Theorem 6. *For the situations considering carbon finance, SCCF and NCF, the reduction rates satisfy*
(a) For the manufacturer, if $m > m_3$, *then* $\widetilde{\Gamma}_M^{SCCF} > \widetilde{\Gamma}_M^{NCF}$; *otherwise,* $\widetilde{\Gamma}_M^{SCCF} \le \widetilde{\Gamma}_M^{NCF}$, *where* $m_3 = \frac{3be_R^2 p_c^2 (1+r)}{8(2-r)}$.
(b) For the retailer, $\widetilde{\Gamma}_R^{SCCF} > \widetilde{\Gamma}_R^{NCF}$;
(c) For the supply chain, $\widetilde{\Gamma}_{SC}^{SCCF} > \widetilde{\Gamma}_{SC}^{NCF}$.

In the retailer-dominated supply chain, the whole supply chain's emission reduction rate is always larger in SCCF than that in NCF. Especially, when the carbon reduction cost coefficient is relatively large ($m > m_3$), both the manufacturer and the retailer have higher emission reduction rate in SCCF. Therefore, supply chain carbon finance can help reduce carbon emissions in the supply chain. With Theorem 3, we can know that in the manufacturer-dominated case, the supply chain's emission reduction rate is always larger in SCCF than that in NCF only when $m > m_2$. Therefore, from the perspective of emission reduction efficiency, it is better for the government to promote the supply chain carbon finance model in the retailer-dominated supply chain. In the manufacturer-dominated supply chain, the government should promote different carbon financial models according to the characteristics of different industries.

5. Numerical Analysis

Numerical experiments are conducted in this section to gain some managerial insights. We concentrate on the comparison among different models presented in Section 4. Let $a = 100$, $b = 1$, $T_R = 100$, $T_M = 100$, $p_c = 1$, $c = 0$, $r = 0.1$, $N = 100$, $e_M = 1$, and $e_R = 1$.

5.1. Impact of *m* on Optimal Emission Reduction Rate

Figure 7 shows the impact of carbon reduction cost coefficient on emission reduction rate among different modes. With the increase of carbon reduction cost coefficient, supply chain's emission reduction rate decreases. As shown in Figure 7, the emission reduction rate under FC mode is the highest. Besides, the emission reduction rate under supply chain carbon finance is significantly larger than that with any cooperation.

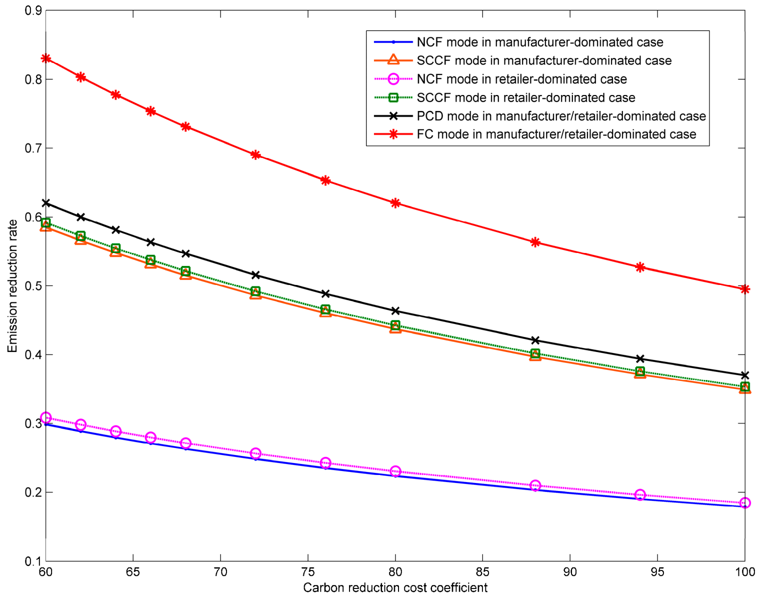

Figure 7. Effects of m on supply chain's emission reduction rate.

When consider the NFC mode and the SCCF mode, we find that the emission reduction rate in the manufacturer-dominated supply chain is lower than that in retailer-dominated supply chain. In other words, supply chain carbon finance has better performance when the retailer is the leader. From a managerial insight, the government can motivate the development of retailer-dominated supply chains so as to improve emission reduction efficiency and reduce total carbon emissions.

When considering the comparison on emission reduction rate between SCCF and PCD mode, it is shown that the emission reduction rate in PCD is always higher than that in SCCF. We can also find that the emission reduction rate in PCD is also higher than that in NCF. From Theorem 4, we can also know that both the supply chain profit and emission reduction rate under the FC situation is higher than that in the PCD situation. Therefore, we can conclude that the cooperation between supply chain members can effectively motivate them to reduce carbon emissions. The government should construct an enterprise credit system to create a suitable business environment for enterprises. It can also promote low-carbon development and reduce the total carbon emissions of society.

5.2. Impact of m on Optimal Profits

Figures 8 and 9 depict the curves of optimal supply chain profits in different model with respect to carbon reduction cost coefficient. They illustrate that the carbon reduction cost coefficient has little or no effect on supply chain profit when a firm has larger reduction cost. Due to the cap-and-trade scheme, a firm can freely buy or sell quotas on the carbon market. So when the per unit reduction cost is larger than the carbon trading price, which may cause by expensive facilities or some other factors, a firm will buy quotas on carbon market rather than deciding on a low reduction rate. This reminds us that the cap-and-trade scheme is not perfect. Sometimes it cannot force a firm to restructure and upgrade to reduce carbon emissions. To avoid this, governments should formulate a proper pricing method for carbon trading prices. Furthermore, how to decide the initial carbon quotas will also affect the reduction strategy of a firm.

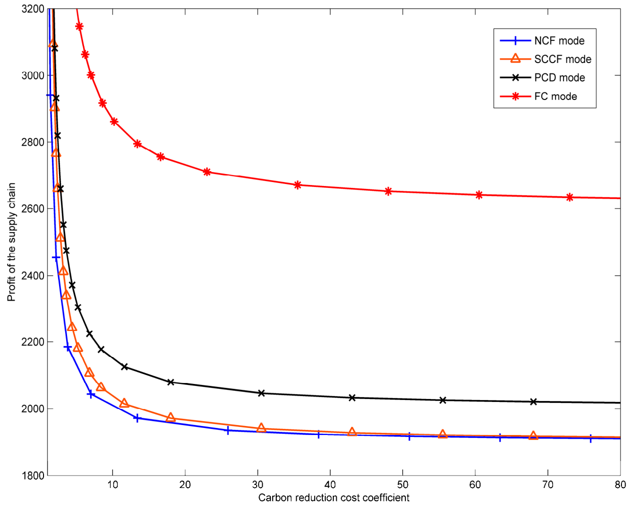

Figure 8. Effects of m on supply chain's profit under a manufacturer-dominated case.

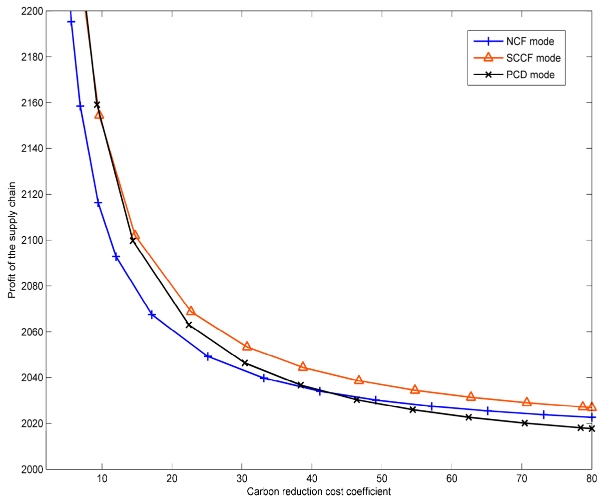

Figure 9. Effects of m on supply chain's profit under retailer-dominated case.

The above two figures also provide the comparison on supply chain profits between SCCF and PCD mode. Figure 8 shows that the supply chain's profit in situation FC is larger than that in situation PCD, which can verify the conclusion in Theorem 4. With Lemma 3 and Table 4, we can know that the values of Π_{SC}^{PCD} and $\widetilde{\Pi}_{SC}^{PCD}$ are the same. In both the manufacturer-dominated and retailer-dominated supply chains, the profit under supply chain carbon finance is higher than that in PCD mode. Thus, we can conclude that the adoption of a supply chain carbon finance model is the best choice in the absence of complete cooperation.

6. Conclusions

June in 2016 was the 14th consecutive month of record high heat for land and oceans. If temperatures continue rising, 2016 will be hottest year ever recorded. Therefore, it is becoming increasingly urgent to further investigate low-carbon development. Failing to invest in low carbon infrastructure will lock in high emissions and vulnerability to the multiple impacts of climate change, leaving a legacy of buildings, roads, energy generation and more which will be expensive to adapt in the future. We research supply chain carbon finance patterns to help firms get green loans from the bank.

In this paper, we study the impact of different financial methods and cooperative levels on the supply chain profit and reduction rate. A two-echelon supply chain with one capital constraint member is explored. The manufacturer-dominated case is considered first as a benchmark. The first strategy is external financing, i.e., the green loan and SCCF. The second is internal financing, i.e., delay-in-payment. Four illustrative models are established: non-cooperation and traditional carbon finance, partial-cooperation and supply chain carbon finance, partial-cooperation and delay-in-payment, and full-cooperation. Our findings demonstrate that SCCF can reduce financial costs and improve the supply chain profit compared to the traditional carbon finance pattern on some occasions. The SMEs and capital-intensive industries can use SCCF to solve their capital constraint problems. For firms, they should clearly indicate the status of industry and their own status by selecting a suitable level of cooperation and financing method. A high cooperation level can improve profit, but it is not always the right fit for a given firm. For governments, a cap-and-trade scheme is a good policy to control emissions of greenhouse gases. However, they should formulate a series of carbon finance policies, such as green loans and carbon funds, to help firms reduce their emissions. In addition, we also analyze the retailer-dominated case. It is interesting to find that the emission reduction rate of the whole supply chain in SCCF is always larger than that in NCF, which is different from the manufacturer-dominated case. Thus, it is better for the government to promote the SCCF mode in the retailer-dominated supply chain. By contrast, in the manufacturer-dominated supply chain, the government should promote different carbon financial models according to the characteristics of different industries.

This research can be extended in several directions. First, this paper only considers the profit of the supply chain. A firm's priority target is maximizing its own profit. Entrepreneurs only makes changes with increasing profit. Researchers can analyze and present a corresponding stable profit allocation which can increase the profits of both sides. Second, supply chain structure in reality is more complex than the models in this paper. There may be more commercial subjects such as logistics service providers and distribution. Further research might be able to build up a more exact model to reflect the true state of supply chain. Third, SCCF also has some weaknesses. For example, if one firm goes bankrupt, all the firms in the supply chain will take a risk because SCCF treats the whole supply chain as a credit bundle. Such risk will cause firms to worry about SCCF. Further study can focus on risk management.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A.

Appendix A.1. Proof of Lemma 1

As we know, the retailer's target and the manufacturer's target are maximizing their profit.

$$\Pi_R = (p-w)Q - \frac{1}{2}m\Gamma^2{}_R + T_R p_c - Lr - Nr, \Pi_M = (w-c)Q - \frac{1}{2}m\Gamma^2{}_M + T_M p_c.$$

Let $\frac{\partial \Pi_R}{\partial p} = 0$, we can get $p^{NCF} = \frac{a+b[e_R p_c(1-\Gamma_R)+w(1+r)]}{2b}$.

Substituting the above value of p^{NCF} into the profit of manufacturer and letting $\frac{\partial \Pi_M}{\partial w} = 0$, we get

$$w^{NCF} = \frac{\left\{a + bc(1+r) - be_R p_c\left(1-\Gamma_R^{NCF}\right) + b(1+r)e_M p_c\left(1-\Gamma_M^{NCF}\right)\right\}}{2b(1+r)}.$$

Substituting the above value of w^{NCF} into p^{NCF},

$$p^{NCF} = \frac{\left\{3a + bc(1+r) + bp_c\left[e_R\left(1-\Gamma_R^{NCF}\right) + e_M(1+r)\left(1-\Gamma_M^{NCF}\right)\right]\right\}}{4b}.$$

Substituting the above value of p^{NCF} and w^{NCF} into the profit of retailer and manufacturer and letting $\frac{\partial \Pi_M}{\partial \Gamma_M} = 0$ and $\frac{\partial \Pi_R}{\partial \Gamma_R} = 0$, we get

$$\begin{cases} \Gamma_R^{NCF} = \dfrac{e_R p_c\{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\}}{8m(1+r) - bp_c^2\left[e_R^2 + 2e_M^2(1+r)^2\right]} \\ \Gamma_M^{NCF} = \dfrac{2e_M p_c\{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\}}{8m(1+r) - bp_c^2\left[e_R^2 + 2e_M^2(1+r)^2\right]} \end{cases}.$$

Appendix A.2. Proof of Lemma 2

In this situation, the retailer's target and the manufacturer's target are maximizing their profit in the second stage. Let $\frac{\partial \Pi_R}{\partial p} = 0$, we can get $p^{SCCF} = \frac{a+b[e_R p_c(1-\Gamma_R)+w(1+r)]}{2b}$.

Substituting the above value of p^{SCCF} into the profit of manufacturer and letting $\frac{\partial \Pi_M}{\partial w} = 0$, we get

$$w^{SCCF} = \frac{\left\{a + bc(1+r) + bp_c\left[-e_R\left(1-\Gamma_R^{SCCF}\right) + e_M\left(1-\Gamma_M^{SCCF}\right)(1+r)\right]\right\}}{2b(1+r)}.$$

Substituting the above value of w^{SCCF} into p^{SCCF},

$$p^{SCCF} = \frac{\left\{3a + bc(1+r) + bp_c\left[e_R\left(1-\Gamma_R^{SCCF}\right) + e_M(1+r)\left(1-\Gamma_M^{SCCF}\right)\right]\right\}}{4b}.$$

Since they take SCCF, they will make reduction decision for the same profit function. So the target is maximizing the supply chain profit in the first stage.

$$\max \Pi_{SC}^{SCCF} = (p-c)Q + (T_M + T_R)p_c - \frac{1}{2}m\Gamma^2{}_M - \frac{1}{2}m\Gamma^2{}_R - Lr - Nr.$$

Substituting the above value of p^{SCCF} and w^{SCCF} into the profit of retailer and manufacturer and letting $\frac{\partial \Pi_{SC}^{SCCF}}{\partial \Gamma_M} = 0$ and $\frac{\partial \Pi_{SC}^{SCCF}}{\partial \Gamma_R} = 0$, we get

$$\begin{cases} \Gamma_R^{SCCF} = \dfrac{e_R p_c (3+\mathrm{r})\{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\}}{8m(1+r)^2 - bp_c^2(3+\mathrm{r})[e_R^2 + e_M^2(1+\mathrm{r})^3]} \\ \Gamma_M^{SCCF} = \dfrac{(1+r)^2(3+r)e_M p_c\{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\}}{8m(1+r)^2 - bp_c^2(3+\mathrm{r})[e_R^2 + e_M^2(1+\mathrm{r})^3]} \end{cases}.$$

The Hessian matrix of Π_{SC}^{SCCF} is

$$\begin{vmatrix} \frac{\partial^2 \Pi_{SC}^{SCCF}}{\partial \Gamma_R^2} & \frac{\partial^2 \Pi_{SC}^{SCCF}}{\partial \Gamma_R \partial \Gamma_M} \\ \frac{\partial^2 \Pi_{SC}^{SCCF}}{\partial \Gamma_M \partial \Gamma_R} & \frac{\partial^2 \Pi_{SC}^{SCCF}}{\partial \Gamma_M^2} \end{vmatrix} = \frac{m\left\{8m(1+r)^2 - bp_c^2(3+r)[e_R^2 + e_M^2(1+r)^3]\right\}}{8(1+r)}.$$

Because $\Gamma_R^{SCCF} > 0$, then

$$8m(1+r)^2 - bp_c^2(3+r)[e_R^2 + e_M^2(1+r)^3] > 0,$$

and

$$\begin{vmatrix} \frac{\partial^2 \Pi_{SC}^{HCF}}{\partial \Gamma_R^2} & \frac{\partial^2 \Pi_{SC}^{HCF}}{\partial \Gamma_R \partial \Gamma_M} \\ \frac{\partial^2 \Pi_{SC}^{HCF}}{\partial \Gamma_M \partial \Gamma_R} & \frac{\partial^2 \Pi_{SC}^{HCF}}{\partial \Gamma_M^2} \end{vmatrix} = \frac{m\left\{8m(1+r)^2 - bp_c^2(3+r)[e_R^2 + e_M^2(1+r)^3]\right\}}{8(1+r)} > 0.$$

Thus, there is local optimal.

Appendix A.3. Proof of Lemma 3

In this situation, the retailer's target and the manufacturer's target are maximizing their profit in the second stage. Let $\frac{\partial \Pi_R}{\partial p} = 0$, we can get $p^{PCD} = \frac{a + b[w + e_R p_c(1-\Gamma_R)]}{2b}$.

Substituting the above value of p^{PCD} into the profit of manufacturer and letting $\frac{\partial \Pi_M}{\partial w} = 0$, we get

$$w^{PCD} = \frac{a + bc + bp_c\left[-e_R\left(1 - \Gamma_R^{NCD}\right) + e_M\left(1 - \Gamma_M^{HCD}\right)\right]}{2b}.$$

Substituting the above value of w^{PCD} into p^{PCD},

$$p^{PCD} = \frac{\left\{3a + bc + bp_c\left[e_R\left(1 - \Gamma_R^{HCD}\right) + e_M\left(1 - \Gamma_M^{HCD}\right)\right]\right\}}{4b}.$$

Since they take delay-in-payment method, the target is maximizing the supply chain profit in the first stage.

Substituting the above value of p^{PCD} and w^{PCD} into the profit of supply chain and letting $\frac{\partial \Pi_{SC}^{PCD}}{\partial \Gamma_M} = 0$ and $\frac{\partial \Pi_{SC}^{PCD}}{\partial \Gamma_R} = 0$, we get

$$\begin{cases} \Gamma_R^{PCD} = \dfrac{3e_R p_c[a - bc - bp_c(e_R + e_M)]}{8m - 3bp_c^2(e_R^2 + e_M^2)} \\ \Gamma_M^{PCD} = \dfrac{3e_M p_c[a - bc - bp_c(e_R + e_M)]}{8m - 3bp_c^2(e_R^2 + e_M^2)} \end{cases}.$$

The Hessian matrix of Π_{SC}^{PCD} is

$$\begin{vmatrix} \frac{\partial^2 \Pi_{SC}^{PCD}}{\partial \Gamma_R^2} & \frac{\partial^2 \Pi_{SC}^{PCD}}{\partial \Gamma_R \partial \Gamma_M} \\ \frac{\partial^2 \Pi_{SC}^{PCD}}{\partial \Gamma_M \partial \Gamma_R} & \frac{\partial^2 \Pi_{SC}^{PCD}}{\partial \Gamma_M^2} \end{vmatrix} = \frac{m[8m - 3bp_c^2(e_R^2 + e_M^2)]}{8}.$$

Because $\Gamma_R^{PCD} > 0$, then $8m - 3bp_c^2(e_R^2 + e_M^2) > 0$,

$$\begin{vmatrix} \frac{\partial^2 \Pi_{SC}^{PCD}}{\partial \Gamma_R^2} & \frac{\partial^2 \Pi_{SC}^{PCD}}{\partial \Gamma_R \partial \Gamma_M} \\ \frac{\partial^2 \Pi_{SC}^{PCD}}{\partial \Gamma_M \partial \Gamma_R} & \frac{\partial^2 \Pi_{SC}^{PCD}}{\partial \Gamma_M^2} \end{vmatrix} = \frac{m[8m - 3bp_c^2(e_R^2 + e_M^2)]}{8} > 0.$$

Thus, there is a local optimal.

Appendix A.4. Proof of Lemma 4

In this situation, the retailer's target and the manufacturer's target are maximizing profit of supply chain.

$$\max \Pi_{SC}^{FC} = (p - c)Q + (T_M + T_R)p_c - \frac{1}{2}m\Gamma^2{}_M - \frac{1}{2}m\Gamma^2{}_R - Nr.$$

Let $\frac{\partial \Pi_{SC}^{FC}}{\partial p} = 0$, we get

$$p^{FC} = \frac{a + bc + be_M p_c(1 - \Gamma_M) + be_R p_c(1 - \Gamma_R)}{2b}.$$

Substituting the above value of p^{TC} into the profit of supply chain and letting $\frac{\partial \Pi_{SC}^{FC}}{\partial \Gamma_M} = 0$ and $\frac{\partial \Pi_{SC}^{FC}}{\partial \Gamma_R} = 0$, we get

$$\begin{cases} \Gamma_R^{FC} = \dfrac{e_R p_c[a - bc - bp_c(e_M + e_R)]}{2m - bp_c{}^2(e_M^2 + e_R^2)} \\ \Gamma_M^{FC} = \dfrac{e_M p_c[a - bc - bp_c(e_M + e_R)]}{2m - bp_c{}^2(e_M^2 + e_R^2)} \end{cases}.$$

The Hessian matrix of Π_{SC}^{TC} is

$$\begin{vmatrix} \frac{\partial^2 \Pi_{SC}^{FC}}{\partial \Gamma_R^2} & \frac{\partial^2 \Pi_{SC}^{FC}}{\partial \Gamma_R \partial \Gamma_M} \\ \frac{\partial^2 \Pi_{SC}^{FC}}{\partial \Gamma_M \partial \Gamma_R} & \frac{\partial^2 \Pi_{SC}^{FC}}{\partial \Gamma_M^2} \end{vmatrix} = \frac{m[2m - bp_c{}^2(e_M{}^2 + e_R{}^2)]}{2}.$$

Because $\Gamma_R^{FC} > 0$, then $2m - bp_c{}^2(e_M^2 + e_R^2) > 0$,

$$\begin{vmatrix} \frac{\partial^2 \Pi_{SC}^{FC}}{\partial \Gamma_R^2} & \frac{\partial^2 \Pi_{SC}^{FC}}{\partial \Gamma_R \partial \Gamma_M} \\ \frac{\partial^2 \Pi_{SC}^{FC}}{\partial \Gamma_M \partial \Gamma_R} & \frac{\partial^2 \Pi_{SC}^{FC}}{\partial \Gamma_M^2} \end{vmatrix} = \frac{m[2m - bp_c{}^2(e_M{}^2 + e_R{}^2)]}{2} > 0.$$

Thus, there is a local optimal.

Appendix A.5. Proof of Theorem 2

From the proof of Lemma 1, we know that the reduction rates of two firms in the situation NCF are

$$\begin{cases} \Gamma_R^{NCF} = \dfrac{e_R p_c\{a - bc(1 + r) - bp_c[e_R + e_M(1 + r)]\}}{8m(1 + r) - bp_c^2\left[e_R^2 + 2e_M^2(1 + r)^2\right]} \\ \Gamma_M^{NCF} = \dfrac{2e_M p_c\{a - bc(1 + r) - bp_c[e_R + e_M(1 + r)]\}}{8m(1 + r) - bp_c^2\left[e_R^2 + 2e_M^2(1 + r)^2\right]} \end{cases}.$$

Let Γ_R^{NCF} minus Γ_M^{NCF}, we get

$$\Gamma_R^{NCF} - \Gamma_M^{NCF} = \frac{[e_R - 2e_M]p_c\{a - bc(1 + r) - bp_c[e_R + (1 + r)e_M]\}}{8(2 + r)m - bp_c^2[e_R^2 + 2(1 + r)^2 e_M^2]}.$$

So, when $e_R - 2e_M > 0$, $\Gamma_R^{NCF} > \Gamma_M^{NCF}$.

The proofs of other situations are similar to that. Thus, we omit them. For m, we can use the same method to draw the conclusion, so we omit it too.

Appendix A.6. Proof of Theorem 3

From the proofs of Lemmas 1 and 2, we know that the reduction rates of two firms in the situation NCF and SCCF are

$$\begin{cases} \Gamma_R^{NCF} = \dfrac{e_R p_c\{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\}}{8m(1+r) - bp_c^2\left[e_R^2 + 2e_M^2(1+r)^2\right]} \\ \Gamma_M^{NCF} = \dfrac{2e_M p_c\{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\}}{8m(1+r) - bp_c^2\left[e_R^2 + 2e_M^2(1+r)^2\right]} \end{cases}$$

and

$$\begin{cases} \Gamma_R^{SCCF} = \dfrac{\left\{\begin{array}{c} e_R p_c(3+\mathrm{r}) \\ \{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\} \end{array}\right\}}{8m(1+r)^2 - bp_c^2(3+\mathrm{r})[e_R^2 + e_M^2(1+\mathrm{r})^3]} \\ \Gamma_M^{SCCF} = \dfrac{\left\{\begin{array}{c} (1+r)^2(3+r)e_M p_c \\ \{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\} \end{array}\right\}}{8m(1+r)^2 - bp_c^2(3+\mathrm{r})[e_R^2 + e_M^2(1+\mathrm{r})^3]} \end{cases}.$$

Let Γ_R^{SCCF} minus Γ_R^{NCF} and Γ_M^{SCCF} minus Γ_M^{NCF}, we get

$$\begin{cases} \Gamma_R^{SCCF} - \Gamma_R^{NCF} = \dfrac{e_R p_c(1+r)\{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\}\left[16m - be_m^2 p_c^2(3+\mathrm{r})(1-r)(1+r)\right]}{\left\{8m(1+r) - bp_c^2\left[e_R^2 + 2e_M^2(1+r)^2\right]\right\}\left\{8m(1+r)^2 - bp_c^2(3+\mathrm{r})\left[e_R^2 + e_M^2(1+\mathrm{r})^3\right]\right\}} \\ \Gamma_M^{SCCF} - \Gamma_M^{NCF} = \dfrac{e_M p_c(1+\mathrm{r})\{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\}\left[8m(1+r)^3 + be_R^2 p_c^2(3+\mathrm{r})(1-r)\right]}{\left\{8m(1+r) - bp_c^2\left[e_R^2 + 2e_M^2(1+r)^2\right]\right\}\left\{8m(1+r)^2 - bp_c^2(3+\mathrm{r})\left[e_R^2 + e_M^2(1+\mathrm{r})^3\right]\right\}} \end{cases}$$

Because $\Gamma_R^{SCCF} > 0$ and $\Gamma_R^{NCF} > 0$, then

$$\begin{cases} 8m(1+r) - bp_c^2\left[e_R^2 + 2e_M^2(1+r)^2\right] > 0 \\ 8m(1+r)^2 - bp_c^2(3+\mathrm{r})\left[e_R^2 + e_M^2(1+\mathrm{r})^3\right] > 0 \end{cases}.$$

Obviously, $8m(1+r)^3 + be_R^2 p_c^2(1-r)(3+r) > 0$. Thus $\Gamma_M^{HCF} > \Gamma_M^{NCF}$.

Let $m_1 = \frac{be_m^2 p_c^2(3+\mathrm{r})(1-r)(1+r)}{16}$. If $m > m_1$, $\Gamma_R^{SCCF} > \Gamma_R^{NCF}$; If $m \le m_1$, $\Gamma_R^{SCCF} \le \Gamma_R^{NCF}$.

According to the definition, $\Gamma_{SC} = \frac{e_R\Gamma_R + e_M\Gamma_M}{e_R + e_M}$. Thus

$$\begin{aligned} \Gamma_{SC}^{SCCF} - \Gamma_{SC}^{NCF} &= \frac{e_R(\Gamma_R^{SCCF} - \Gamma_R^{NCF}) + e_M(\Gamma_M^{SCCF} - \Gamma_M^{NCF})}{e_R + e_M} \\ &= \frac{p_c(1+r)\{a - bc(1+r) - bp_c[e_R + e_M(1+r)]\}\left\{16me_R^2 + e_m^2\left[8m(1+r)^3 - be_R^2 p_c^2 r(1-r)(3+r)\right]\right\}}{\left\{8m(1+r) - bp_c^2\left[e_R^2 + 2e_M^2(1+r)^2\right]\right\}\left\{8m(1+r)^2 - bp_c^2(3+\mathrm{r})\left[e_R^2 + e_M^2(1+\mathrm{r})^3\right]\right\}} \end{aligned}.$$

Let $m_2 = \frac{be_R^2 e_m^2 p_c^2 r(1-r)(3+r)}{16me_R^2 + 8(1+r)^3 e_m^2}$. If $m > m_2$, $\Gamma_{SC}^{SCCF} > \Gamma_R^{NCF}$; If $m \le m_2$, $\Gamma_R^{SCCF} \le \Gamma_R^{NCF}$.

Appendix A.7. Proof of Theorem 4

From the proofs of Lemmas 3 and 4, we know that the reduction rates of two firms in the situation PCD and FC are

$$\begin{cases} \Gamma_R^{PCD} = \dfrac{3e_R p_c[a - bc - bp_c(e_R + e_M)]}{8m - 3bp_c^2(e_R^2 + e_M^2)} \\ \Gamma_M^{PCD} = \dfrac{3e_M p_c[a - bc - bp_c(e_R + e_M)]}{8m - 3bp_c^2(e_R^2 + e_M^2)} \end{cases} \text{and} \begin{cases} \Gamma_R^{FC} = \dfrac{e_R p_c[a - bc - bp_c(e_M + e_R)]}{2m - bp_c{}^2(e_M^2 + e_R^2)} \\ \Gamma_M^{FC} = \dfrac{e_M p_c[a - bc - bp_c(e_M + e_R)]}{2m - bp_c{}^2(e_M^2 + e_R^2)} \end{cases}.$$

Let Γ_R^{FC} minus Γ_R^{PCD} and Γ_M^{FC} minus Γ_M^{PCD}, we get

$$\begin{cases} \Gamma_R^{FC} - \Gamma_R^{PCD} = \dfrac{2e_R p_c[a - bc - bp_c(e_R + e_M)]}{[8m - 3bp_c^2(e_R^2 + e_M^2)][2m - bp_c{}^2(e_M^2 + e_R^2)]} \geq 0 \\ \Gamma_M^{FC} - \Gamma_M^{PCD} = \dfrac{2e_M p_c[a - bc - bp_c(e_R + e_M)]}{[8m - 3bp_c^2(e_R^2 + e_M^2)][2m - bp_c{}^2(e_M^2 + e_R^2)]} \geq 0 \end{cases}.$$

So $\Gamma_R^{PCD} \leq \Gamma_R^{FC}$, $\Gamma_M^{PCD} \leq \Gamma_M^{FC}$.

Substituting the corresponding values of p^* and w^* into the profit of supply chain of situation PCD and FC, we get

$$\begin{cases} \Pi_{SC}^{PCD} = \left[\frac{12m^2}{b} - \frac{9}{2}mp_c^2(e_R^2 + e_M^2)\right] \dfrac{[a - b(c + p_c e_R + p_c e_M)]^2}{[8m - 3bp_c^2(e_R^2 + e_M^2)]^2} + (G_R + G_M)p_c \\ \Pi_{SC}^{FC} = \left[\frac{m^2}{b} - \frac{1}{2}mp_c^2(e_R^2 + e_M^2)\right] \dfrac{[a - b(c + p_c e_R + p_c e_M)]^2}{[2m - bp_c^2(e_R^2 + e_M^2)]^2} + (G_R + G_M)p_c \end{cases}.$$

Due to $m - bp_c^2(e_R^2 + e_M^2) > 0$ and $4m - 3bp_c^2(e_R^2 + e_M^2) > 0$.

Thus, we can get $\Pi_{SC}^{FC} > \Pi_{SC}^{PCD}$.

Appendix A.8. Proofs of Theorems 5 and 6

The proofs are similar to those of Theorems 2 and 3, thus we omit them.

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