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Cooperation and Pricing Strategy of Enterprises' Carbon Emission Reduction in Different Power Structures

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Abstract: *In the context of carbon emission reduction, different power structures will have an important impact on business decision-making. Based on this, assuming that the consumer demand is affected by the price of low-carbon products and the emission reduction level of node enterprises, this paper constructs seven game models, including the cooperative decision-making model, the Stackelberg game and the vertical Nash game respectively dominated by manufacturers and retailers under non-cooperative decision-making, and the Stackelberg game and the vertical Nash game respectively dominated by manufacturers and retailers under semi cooperative decision-making, then compares and analyzes some optimal decision results of the node enterprises in the supply chain under different game structures, such as product pricing, carbon emission reduction effect and profit level. It is found that the dominant position of enterprises and the cooperative degree among enterprises have significant impact on carbon emission reduction, the profit of enterprise and the supply chain system. The results can be used for reference for the emission reduction and cooperative decision-making of low-carbon enterprises.*

Keywords: *Low-carbon Enterprise, Emission Reduction, Power Structure, Game, Pricing*

1. Introduction

In recent years, global warming and frequent extreme weather events have severely impacted natural resources and ecosystems. Mounting pressures from the greenhouse effect and resource scarcity have highlighted the critical importance of low-carbon supply chain management. Under these circumstances, as supply chain enterprises implement carbon emission reduction initiatives, their operational costs inevitably increase. A pivotal challenge lies in how enterprises with varying degrees of market dominance can optimize operational decisions to enhance performance across supply chain nodes and the entire network. Addressing this issue, this study employs game theory to conduct a comparative analysis of product carbon emission reduction levels and pricing strategies among upstream and downstream enterprises under different power structures – including cooperative, non-cooperative, and semi-cooperative models.

In low-carbon supply chain management, carbon emission reduction and pricing decisions critically affect supply-demand balance and operational efficiency. Tang et al.[1] analyzed pricing and emission decisions under manufacturer/retailer dominance in a two-tier supply chain; Ma et al.[2] demonstrated centralized decision frameworks outperform when low-carbon investment coefficients are extreme, with stability analysis of dynamic game models; Lin et al.[3] proposed side-payment self-enforcing contracts to coordinate supply chains under social preferences; Yu et al. [4] established a manufacturer-led Stackelberg model, revealing manufacturers' preference for revenue-sharing contracts versus retailers' wholesale price prioritization. Sun et al.[5] analyzed carbon transfer effects and technology lag under government policies; Zou et al.[6] identified synergies between CSR and retailer fairness concerns; Dai et al.[7] optimized multi-period subsidy strategies via dynamic programming. However, when upstream and downstream enterprises are in different dominant positions or both are equal in status, it needs to analyze deeply on how to make decisions about product emission reduction and pricing under the form of complete cooperation or incomplete cooperation.

After Benjaafar et al.[8] bringing carbon emissions into the research of low-carbon supply chain,

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some scholars have taken channel behavior theory into account in low-carbon supply chain one after another, and used game theory to study the power structure of supply chain channels.Li et al.[9]established a low-carbon supply chain with a financially constrained manufacturer and retailer, revealing that manufacturer-dominated power structures reduce system profits and emission reduction levels. Cai et al.[10]extended this by modeling three power structures, demonstrating consumer low-carbon preferences enhance social-environmental performance, while carbon trading prices mediate profit impacts. Peng et al.[11]proved government-manufacturer dual incentives optimize emission reduction through principal-agent game models. Liu et al.[12]analyzed optimal strategies in three-tier supply chains involving technology companies under varied ownership structures. Li et al.[13]identified vertical integration (VI) as the optimal model for emission reduction under consumer preferences and carbon taxes. Qiu et al.[14]developed manufacturer/retailer-led Stackelberg models under subsidy-carbon tax policies.However, the power structure involved in the above literature on low-carbon supply chain management does not discuss the degree of cooperation between enterprises, different cooperation modes and degrees will inevitably affect product pricing and emission reduction strategies, especially after consumers' low-carbon preferences are included, how to formulate corresponding strategies when enterprises are in different dominant positions deserves further study.

Based on the above analysis, this article will focus on the two upstream and downstream manufacturing enterprises in different dominant positions, construct three models of cooperative decision-making, non-cooperative decision-making and semi-cooperative decision-making respectively. It will also study the difference between the carbon emission reduction level of each enterprise when the manufacturer is dominant and that of the retailer, whether the pricing strategy of the product is the same, what level the profits of the upstream and downstream enterprises and the overall profits of the supply chain are at, and which decision-making situation is the best for consumers. If both enterprises have equal status, what the above result will be? Which power structure is the best for cooperative emission reduction? These are the problems to be studied in this paper.

2. Model Assumptions and Symbol Appointment

In order to study the impact of consumers' low-carbon preference and enterprises’ carbon emission reduction on supply chain performance, it is assumed that consumers with social responsibility in the current market have preferences for low-carbon products, and there are two manufacturing enterprises in upstream and downstream of the supply chain. Compared with upstream enterprises (manufacturers), downstream enterprises are retailers, but they also have production capacity, hence can be regarded as retail enterprises with certain processing capacity. Both of them are subject to government carbon emission regulations and voluntarily reduce emissions. In view of the low-carbon preference of end consumers in the market, enterprises have to invest in improving technologies to increase carbon emission reduction. In order to maximize the profits, the two enterprises must take carbon emission reduction as a decision variable in addition to decisions about product pricing, and make a choice between self-emission reduction and cooperative emission reduction. In fact, in addition to the commonly recognized strength of manufacturing enterprises in the supply chain, many retail enterprises with processing and manufacturing capabilities may also be in a dominant position, such as Japan's retail giant 7-ELEVEn and Sweden's IKEA. Therefore, this paper will focus on the product pricing, the effect of carbon emission reduction and profit level of upstream and downstream enterprises with different cooperation forms and in different power structures. The research framework of this paper is shown in Figure 1.

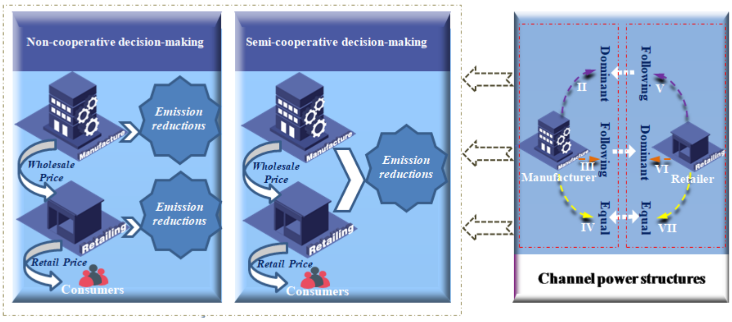

Figure 1: Research framework of cooperation and pricing strategy of enterprises' carbon emission reduction in different power structures

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The relevant symbols and meanings involved in the model are shown in Table 1.

Table 1: The major decision variables and parameters

Parameters	Description
c	Marginal production cost of manufacturer
η	Cost coefficient of carbon emission reduction of products
k	Consumers' low-carbon preference, $k > 0$
a	Market Size
b	Sensitivity coefficient of market demand to retail price
π_M , π_R , π_J	Represents the profits of manufacturers, retailers and supply chain systems respectively
Variables	
w	Manufacturer's wholesale price per unit product
p	Retailer's retail price per unit product
e_i	Carbon emission reduction per unit product; i = m, r represents manufacturer and retailer respectively
Superscript	
$(\ )^I$	The optimal decision under joint decision model (JC Model)
$(\ )^{II}$, $(\ )^{III}$, $(\ )^{IV}$	Represents the optimal decision under MS-NC Model, RS-NC Model and VN-NC Model respectively
$(\ )^{V}$, $(\ )^{VI}$, $(\ )^{VII}$	Represents the optimal decision under MS-SC Model, RS-SC Model and VN-SC Model respectively

The relevant assumptions are as follows:

(1)Using Poyago-Theotoky's research[15] for reference, it is assumed that the relationship between carbon emission reduction cost and carbon emission reduction is $\frac{1}{2}\eta e_i^2$, in which $i = m, r$ represents manufacturers and retailers respectively;

(2)The demand for low-carbon products is co-determined by the price of the product and the carbon emission reduction. The following form of market demand function can be established for different supply chain structures

$$Q = a - bp + k(e_m + e_r)$$

Obviously, $p > c$, so $a - bc > a - bp > 0$;

Therefore, the profit expression of manufacturers and retailers is

$$\pi_M(w, e_m) = (w - c)Q - \frac{1}{2}\eta e_m^2 = (w - c)[a - bp + k(e_m + e_r)] - \frac{1}{2}\eta e_m^2 \tag{1}$$

$$\pi_R(p, e_r) = (p - w)Q - \frac{1}{2}\eta e_r^2 = (p - w)[a - bp + k(e_m + e_r)] - \frac{1}{2}\eta e_r^2 \tag{2}$$

3. Cooperative Decision-making Model (JC Model)

Firstly, a benchmark model is established, that is, manufacturers and retailers in the sustainable supply chain establish a fully trusted cooperative relationship, aiming at maximizing the system profit, and determine the retail price and carbon emission reduction of products through joint decision-making. From equations (1) and (2), the profit expression of the whole supply chain system is

$$\pi_J(p, e_m, e_r) = \pi_M(w, e_m) + \pi_R(p, e_r) = (p - c)[a - bp + k(e_m + e_r)] - \frac{1}{2}\eta(e_m^2 + e_r^2) \tag{3}$$

Under the situation of cooperative decision-making, it can be seen that the following conclusions hold true by using the first-order optimization conditions.

Theorem 3.1 In JC Model, the optimal retail price and the optimal carbon emission reduction per unit product are respectively

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$$p^I = \frac{\eta(a+bc)-2k^2c}{2b\eta-2k^2}, e_m{}^I = e_r{}^I = \frac{k(a-bc)}{2b\eta-2k^2}.$$

Based on the above analysis, it can be seen that the product demand in JC Model $Q^I = b\eta(a-bc)/(2b\eta-2k^2) \geq 0$, combining with the previous $a-bc>0$, hence $b\eta-k^2>0$. Next, the influence of consumer's low carbon preference level (k) on product carbon emission reduction e_m (or e_r) can be given.

Theorem 3.2 In JC Model, whether manufacturers or retailers, the carbon emission reduction of their products will increase with the increase of consumers' low-carbon preference level, that is

$$\frac{\partial e_m^I}{\partial k} = \frac{\partial e_r^I}{\partial k} = \frac{(2b\eta+2k^2)(a-bc)}{(2b\eta-2k^2)^2} > 0.$$

Theorem3.1 shows that there is a unique optimal solution when upstream and downstream enterprises make joint decisions based on the cooperation framework. The retail price and emission reduction of its products are affected by factors such as consumers' low-carbon preference level and carbon emission reduction cost coefficient. At the same time, from Theorem 3.2, it can also be found that when consumers' preference for low-carbon products increases, low-carbon enterprises will increase the carbon emission reduction of products, which shows that the increase of consumers' preference for low-carbon products is transmitted to the income function of enterprises through the increase of demand, thus affecting their decision-making behavior.

4. Non-cooperative Decision-making Model (NC Model)

In NC Model, manufacturers and retailers make their own decisions on carbon emission reductions and product prices. For upstream and downstream enterprises that may be in different power structures, this paper focuses on the analysis of their game models with complete information, and compares the equilibrium results of different game models. See Figure 2.

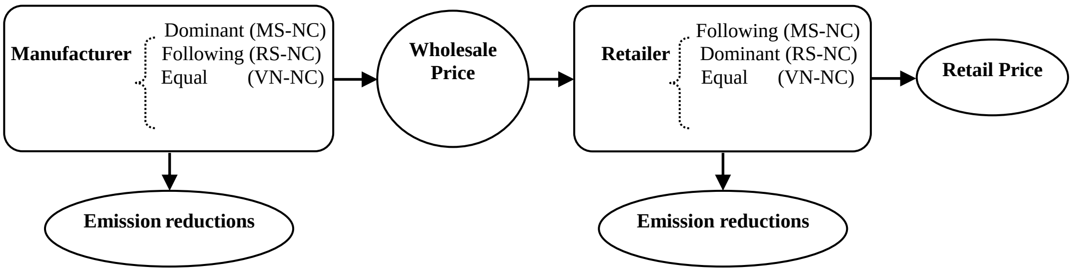

Figure 2 : Three game structures under non-cooperative decision-making.

4.1 Stackelberg Game of Manufacture (MS-NC Model)

If the current supply chain system consists of a large-scale manufacturer and a small-scale retailer, the game between the two is divided into two stages, the first stage is about emission reduction, the second stage is about product price, and in the Stackelberg game in the second stage, the manufacturer is the dominant party and the retailer is the following party.

The following is a solution by reverse induction. First, it studies the product price. For equation (2), according to the first-order optimization conditions, the retailer's optimal response function to the retail price is determined as follows:

$$p = \frac{1}{2b}[a+bw+k(e_m+e_r)]$$

Substituting the above results into equation (1), the manufacturer can determine the wholesale price of its products according to the maximization of its own profits

$$\tilde{w} = \frac{1}{2b}[a+bc+k(e_m+e_r)] \tag{4}$$

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Therefore, retailers sell their products at

$$\tilde{p} = \frac{1}{4b}[3a + bc + 3k(e_m + e_r)] \tag{5}$$

Then, substituting the product prices of the manufacturer and the retailer $\tilde{p}$ and $\tilde{w}$ into the profit expressions (1) and (2), finding the second-order partial derivative of the emission reduction respectively, and giving the following Hessen matrix

$$H_{MS-NC} = \begin{pmatrix} \frac{k^2 - 4b\eta}{4b} & \frac{k^2}{4b} \\ \frac{k^2}{8b} & \frac{k^2 - 8b\eta}{8b} \end{pmatrix}.$$

From $b\eta - k^2 > 0$, it is easily known that

$$(-1)\det H_{MS-NC} = -\frac{k^2 - 4b\eta}{4b} > 0, \quad (-1)^2 \det H_{MS-NC} = \frac{\eta(8b\eta - 3k^2)}{8b} > 0,$$

so that Hessian matrix H_{MS-NC} is negative.

Simultaneously to solve the equations $\frac{\partial \pi_M}{\partial e_m} = 0$ and $\frac{\partial \pi_R}{\partial e_r} = 0$, the optimal emission reductions of upstream and downstream enterprises can be obtained, then substitute them back into formulas (4) and (5), the optimal selling price of their products can be determined. See Theorem 4.1 for specific results.

Theorem 4.1 In MS-NC Model, the optimal wholesale price and retail price per unit product, and the optimal carbon emission reduction of manufacturers and retailers are respectively

$$w^{II} = \frac{4\eta(a+bc) - 3k^2c}{8b\eta - 3k^2},\ p^{II} = \frac{2\eta(3a+bc) - 3k^2c}{8b\eta - 3k^2},\ e_m{}^{II} = \frac{2k(a-bc)}{8b\eta - 3k^2},\ e_r{}^{II} = \frac{k(a-bc)}{8b\eta - 3k^2}.$$

Theorem 4.2 Similar to Theorem 3.2, under MS-NC Model, the carbon emission reduction of products of both manufacturers and retailers will increase with the increase of consumers' low-carbon preference level, that is,

$$\frac{\partial e_m^{II}}{\partial k} = \frac{2(8b\eta + 3k^2)(a-bc)}{(8b\eta - 3k^2)^2} > 0,\ \frac{\partial e_r^{II}}{\partial k} = \frac{(8b\eta + 3k^2)(a-bc)}{(8b\eta - 3k^2)^2} > 0.$$

4.2 Stackelberg Game of Retailer (RS-NC Model)

Assuming that there is a strong retailer controlling current market, that is, the retailer dominates and the manufacturer follows, it will use Stackelberg game analyze the pricing decision in the second stage. In RS-NC Model, the paper introduces the concept of marginal profit (ρ) to replace the decision variable of retail price: $p = w + \rho$. According to the above description, the profit expressions (1) and (2) for manufacturers and retailers can be rewritten to

$$\pi_M(w, e_m) = (w - c)[a - b(w + \rho) + \mathrm{k}(e_m + e_r)] - \frac{1}{2}\eta e_m{}^2 \tag{6}$$

$$\pi_R(\rho, e_r) = \rho[a - b(w + \rho) + k(e_m + e_r)] - \frac{1}{2}\eta e_r{}^2 \tag{7}$$

In the following, the inverse order induction method is used to examine the product price. For Equation (6), according to the first-order optimization conditions, the manufacturer's optimal response function on the wholesale price is determined $w = \frac{1}{2b}[a + bc - b\rho + k(e_m + e_r)]$.

Substituting the above results into Equation (7), the retailer can determine its marginal profit based on its own profit maximization

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$$\tilde{\rho} = \frac{1}{2b}[a - bc + k(e_m + e_r)] \tag{8}$$

It is known that the selling price of the manufacturer's products is

$$\tilde{w} = \frac{1}{4b}[a + 3bc + k(e_m + e_r)] \tag{9}$$

Correspondingly, the retailer's product is sold at a price of

$$\tilde{p} = \tilde{w} + \tilde{\rho} = \frac{1}{4b}[3a + bc + 3k(e_m + e_r)] \tag{10}$$

Then substituting the above formulas (8) and (9) into the profit expressions (6) and (7), calculating the second-order partial derivative of the emission reduction respectively, giving the Hessian matrix H_{RS-NC}, combining $b\eta - k^2 > 0$, and it is easy to know that the Hessian matrix H_{RS-NC} is negative. Simultaneously to solve the equations $\frac{\partial \pi_M}{\partial e_m} = 0$ and $\frac{\partial \pi_R}{\partial e_r} = 0$, the optimal emission reductions of upstream and downstream enterprises can be obtained, then substitute them back into formulas (9) and (10), the optimal selling price of their products can be determined. See Theorem 4.3 for specific results.

Theorem 4.3 In RS-NC Model, the optimal wholesale price and retail price per unit product, as well as the optimal carbon emission reduction of manufacturers and retailers are respectively

$$w^{III} = \frac{2\eta(a+3bc) - 3k^2 c}{8b\eta - 3k^2},\ p^{III} = \frac{2\eta(3a+bc) - 3k^2 c}{8b\eta - 3k^2},\ e_m{}^{III} = \frac{k(a-bc)}{8b\eta - 3k^2},\ e_r{}^{III} = \frac{2k(a-bc)}{8b\eta - 3k^2}.$$

According to Theorem 4.3, it is easy to know that

$$\frac{\partial e_m^{III}}{\partial k} = \frac{(8b\eta + 3k^2)(a-bc)}{(8b\eta - 3k^2)^2} > 0,\quad \frac{\partial e_r^{III}}{\partial k} = \frac{2(8b\eta + 3k^2)(a-bc)}{(8b\eta - 3k^2)^2} > 0.$$

Therefore, the impact of consumers' low-carbon preference level on product carbon emission reduction is consistent with the results of Theorem 3.2 and Theorem 4.2, which will not be repeated later.

4.3 Vertical Nash Game (VN-NC Model)

When manufacturers and retailers have equal status, bear their carbon emission reduction costs and make independent decisions respectively at the same time, for the profit expressions (6) and (7) of both parties, the first-order optimization conditions are used. Simultaneously to solve the equations $\frac{\partial \pi_M}{\partial w} = 0$ and $\frac{\partial \pi_R}{\partial \rho} = 0$, the optimal response function of manufacturers and retailers on price or marginal profit can be obtained

$$\tilde{w} = \frac{1}{3b}[a + 2bc + k(e_m + e_r)] \quad \tilde{\rho} = \frac{1}{3b}[a - bc + k(e_m + e_r)] \tag{11}$$

Then the above optimal response function is substituted into expressions (6) and (7), simultaneously to solve the equations $\frac{\partial \pi_M}{\partial e_m} = 0$ and $\frac{\partial \pi_R}{\partial e_r} = 0$, then combine $p = w + \rho$,the following theorem can be given.

Theorem 4.4 In VN-NC Model, the optimal wholesale price and retail price per unit product, as well as the optimal carbon emission reduction of manufacturers and retailers are respectively

$$w^{IV} = \frac{3\eta(a+2bc) - 4k^2 c}{9b\eta - 4k^2},\ p^{IV} = \frac{3\eta(2a+bc) - 4k^2 c}{9b\eta - 4k^2},\ e_m{}^{IV} = e_r{}^{IV} = \frac{2k(a-bc)}{9b\eta - 4k^2}.$$

Theorem 4.5 The results of the three game models (MS-NC, RS-NC, VN-NC) under non-cooperative decision-making are compared as follows

(1) $w^{II} > w^{IV} > w^{III}$; (2) $p^{II} = p^{III} > p^{IV}$; (3) $e_m^{II} > e_m^{IV} > e_m^{III}$; (4) $e_r^{III} > e_r^{IV} > e_r^{II}$.

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From Theorem 4.5, it can be seen that under non-cooperative decision-making, the wholesale price and carbon emission reduction of products are the highest when manufacturers dominate, while the retail price and carbon emission reduction of products are the highest when retailers dominate, which means, the game result for the upstream and downstream enterprises in different power structures is that the one who dominates is the one who prevails over. If the two sides are equal, then the wholesale price of products and carbon emission reduction are in the middle level, and the price of products is the best for consumers at this time.

5. Semi-cooperative Decision-making Model (SC Model)

In the semi-cooperative decision-making model, manufacturers and retailers jointly make decisions on carbon emission reduction (the first stage), but each makes decisions on the price of its products (the second stage). That is, the game in the second stage can be analyzed by referring to the corresponding situation of non-cooperative decision-making (NC Model). See Figure 3.

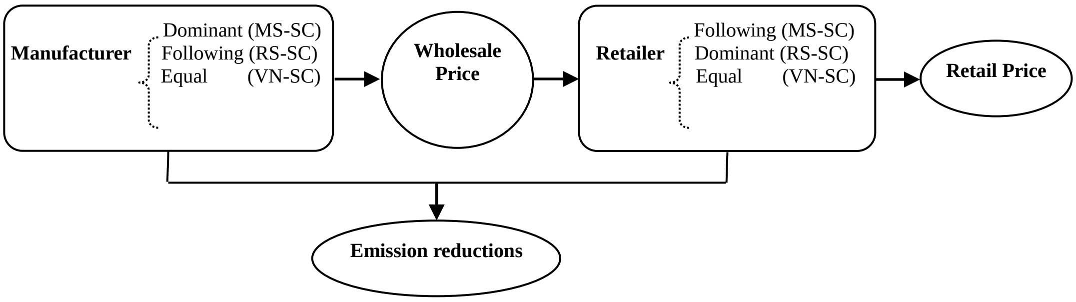

Figure 3: Three game structures under semi-cooperative decision-making.

5.1 When Manufactures Dominate (MS-SC Model)

With regard to the price game in the second stage, the result is equivalent to Equations (4) and (5) in MS-NC Model. Next, it will examine the joint decision of manufacturers and retailers on emission reduction in the first stage, and substitute the $\tilde{p}$ in expression (5) into the profit expression (3) of the supply chain system, and there are

$$\pi_J(e_m,e_r)=(\tilde{p}-c)[a-b\tilde{p}+k(e_m+e_r)]-\frac{1}{2}\eta(e_m{}^2+e_r{}^2)=\frac{3}{16b}[a-bc+k(e_m+e_r)]^2-\frac{1}{2}\eta(e_m{}^2+e_r{}^2)$$

Simultaneously to solve the equations $\frac{\partial\pi_J(e_m,e_r)}{\partial e_m}=0$ and $\frac{\partial\pi_J(e_m,e_r)}{\partial e_r}=0$, after substituting the results into formulas (4) and (5), the MS-SC Model can be obtained, and the optimal wholesale price and retail price of a unit product, as well as the optimal carbon emission reduction of manufacturers and retailers are respectively

$$w^V=\frac{2\eta(a+bc)-3k^2c}{4b\eta-3k^2},\quad p^V=\frac{\eta(3a+bc)-3k^2c}{4b\eta-3k^2},\quad e_m{}^V=e_r{}^V=\frac{3k(a-bc)}{8b\eta-6k^2}$$

5.2 When Retailers Dominate (RS-SC Model)

According to the profit expressions (6) and (7), the profit expression of the supply chain system is

$$\pi_J(e_m,e_r)=(\tilde{w}-c+\tilde{\rho})[a-b(\tilde{w}+\tilde{\rho})+k(e_m+e_r)]-\frac{1}{2}\eta(e_m{}^2+e_r{}^2) \tag{12}$$

With regard to the price game in the second stage, the result is equivalent to Equations (8) and (9) in RS-NC Model. Next, it will examine the joint decision of manufacturers and retailers on emission reduction in the first stage, then substitute $\tilde{\rho}$ and $\tilde{w}$ of equations (8) and (9) into the system profit expression (12) respectively, and get the following:

$$\pi_J(e_m,e_r)=\frac{3}{16b}[a-bc+k(e_m+e_r)]^2-\frac{1}{2}\eta(e_m{}^2+e_r{}^2).$$

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Simultaneously to solve the equations $\frac{\partial \pi_J(e_m, e_r)}{\partial e_m} = 0$ and $\frac{\partial \pi_J(e_m, e_r)}{\partial e_r} = 0$, after substituting the results into formulas (9) and (10), the RS-SC Model can be obtained, and the optimal wholesale price and retail price of a unit product, as well as the optimal carbon emission reduction of manufacturers and retailers are respectively

$$w^{VI} = \frac{\eta(a+3bc)-3k^2c}{4b\eta-3k^2},\quad p^{VI} = \frac{\eta(3a+bc)-3k^2c}{4b\eta-3k^2},\quad e_m{}^{VI} = e_r{}^{VI} = \frac{3k(a-bc)}{8b\eta-6k^2}.$$

5.3 When Manufactures and Retailers are Equal (VN-SC Model)

If manufacturers and retailers are equal, then in the first stage of semi-cooperative decision-making, both parties jointly decide the carbon emission reduction, but in the second stage, they independently decide the selling price of their products, and the best response function of manufacturers and retailers on price or marginal profit in independent decision-making is the Equation (11) in VN-NC Model. It can be obtained by substituting Equation (11) into System Profit Expression (12)

$$\pi_J(e_m, e_r) = (\tilde{w} - c + \tilde{\rho})[a - b(\tilde{w} + \tilde{\rho}) + k(e_m + e_r)] - \frac{1}{2}\eta(e_m{}^2 + e_r{}^2)$$

$$= \frac{2}{9b}[a - bc + k(e_m + e_r)]^2 - \frac{1}{2}\eta(e_m{}^2 + e_r{}^2).$$

Simultaneously to solve the equations $\frac{\partial \pi_J(e_m, e_r)}{\partial e_m} = 0$ and $\frac{\partial \pi_J(e_m, e_r)}{\partial e_r} = 0$, after substituting the results into formula (11), then combining $p = w + \rho$, the VN-SC Model can be obtained, and the optimal wholesale price and retail price of a unit product, as well as the optimal carbon emission reduction of manufacturers and retailers are respectively

$$w^{VII} = \frac{3\eta(a+2bc)-8k^2c}{9b\eta-8k^2},\quad p^{VII} = \frac{3\eta(2a+bc)-8k^2c}{9b\eta-8k^2},\quad e_m{}^{VII} = e_r{}^{VII} = \frac{4k(a-bc)}{9b\eta-8k^2}.$$

Theorem 5.1 The results of the three game models (MS-SC, RS-SC, VN-SC) under semi-cooperative decision-making are compared as follows

(1) When $b\eta > \frac{7}{6}k^2$, $w^V > w^{VII} > w^{VI}$; when $\frac{9}{8}k^2 < b\eta < \frac{7}{6}k^2$, $w^{VII} > w^V > w^{VI}$;

(2) $p^V = p^{VI} < p^{VII}$; (3) $e_m^V = e_m^{VI} < e_m^{VII}$; (4) $e_r^V = e_r^{VI} < e_r^{VII}$.

Theorem 5.1 shows that when upstream and downstream enterprises have equal status, the carbon emission reduction made by joint decision reaches the highest level, and the vertical cooperative emission reduction adopted at this time is obviously the optimal decision, which not only meets the low-carbon consumption preference, but also significantly increases the retail price of products. Because in the case of semi-cooperation, carbon emission reduction is jointly decided, so whoever is dominant, the carbon emission reduction of products of both sides is consistent, and the retail price of products is also at a low level. But when retailers dominate, they will get the lowest wholesale price of products, which is consistent with the result of Theorem 4.5, while when manufacturers dominate, the wholesale price of products will fluctuate under the influence of carbon emission reduction cost coefficient, consumers' price sensitivity coefficient and low carbon preference level. It can be seen that at this time, when the upstream and downstream enterprises have equal status, it is most conducive to promoting cooperation between enterprises of both sides to improve carbon emission reduction.

Theorem 5.2 Under the three decision-making situations of cooperation, non-cooperation and semi-cooperation, the comparison results of carbon emission reduction of enterprises under different power structures are as follows:

$$e_m^I = e_r^I > e_m^{VII} = e_r^{VII} > e_m^V = e_r^V = e_m^{VI} = e_r^{VI} > e_m^{II} = e_r^{III} > e_m^{IV} = e_r^{IV} > e_m^{III} = e_r^{II}.$$

As seen from Theorem 5.2, Enterprises have the largest carbon emission reduction under cooperative decision-making, and that in semi-cooperative decision-making is the next. However, in

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the case of non-cooperative decision-making, the carbon emission reduction of retailers under the situations where manufacturers dominate and that of manufacturers under the situations where retailers dominate are at the lowest level, which shows that the enterprises in the follower are obviously not active in reducing emissions during non-cooperative decision-making, and the power structure has a significant impact on the emission reduction level of enterprises.

According to the equilibrium results under three different decision situations, the optimal profits of each node enterprise and supply chain system under seven corresponding models are listed, as shown in Table 2.

Table 2: Optimal profits of node enterprises and supply chain system under different decision-making situations.

Model	π_M	π_R	π_J
JC(I)	–	–	$\frac{\eta(a-bc)^2}{4(b\eta-k^2)}$
MS-NC(II)	$\frac{2\eta(4b\eta-k^2)(a-bc)^2}{(8b\eta-3k^2)^2}$	$\frac{\eta(8b\eta-k^2)(a-bc)^2}{2(8b\eta-3k^2)^2}$	$\frac{\eta(24b\eta-5k^2)(a-bc)^2}{2(8b\eta-3k^2)^2}$
RS-NC(III)	$\frac{\eta(8b\eta-k^2)(a-bc)^2}{2(8b\eta-3k^2)^2}$	$\frac{2\eta(4b\eta-k^2)(a-bc)^2}{(8b\eta-3k^2)^2}$	$\frac{\eta(24b\eta-5k^2)(a-bc)^2}{2(8b\eta-3k^2)^2}$
VN-NC(IV)	$\frac{\eta(9b\eta-2k^2)(a-bc)^2}{(9b\eta-4k^2)^2}$	$\frac{\eta(9b\eta-2k^2)(a-bc)^2}{(9b\eta-4k^2)^2}$	$\frac{2\eta(9b\eta-2k^2)(a-bc)^2}{(9b\eta-4k^2)^2}$
MS-SC(V)	$\frac{\eta(16b\eta-9k^2)(a-bc)^2}{8(4b\eta-3k^2)^2}$	$\frac{\eta(8b\eta-9k^2)(a-bc)^2}{8(4b\eta-3k^2)^2}$	$\frac{3\eta(a-bc)^2}{4(4b\eta-3k^2)}$
RS-SC(VI)	$\frac{\eta(8b\eta-9k^2)(a-bc)^2}{8(4b\eta-3k^2)^2}$	$\frac{\eta(16b\eta-9k^2)(a-bc)^2}{8(4b\eta-3k^2)^2}$	$\frac{3\eta(a-bc)^2}{4(4b\eta-3k^2)}$
VN-SC(VII)	$\frac{\eta(a-bc)^2}{9b\eta-8k^2}$	$\frac{\eta(a-bc)^2}{9b\eta-8k^2}$	$\frac{2\eta(a-bc)^2}{9b\eta-8k^2}$

Comparing the optimal profits in Table 2, it is easy to know that the following theorems hold true.

Theorem 5.3 (1) Comparison of profits of enterprises at each node.

①Under Non-cooperative Decision-making:

$\pi_M^{IV}=\pi_R^{IV}>\pi_M^{III}=\pi_R^{II}$, $\pi_M^{II}=\pi_R^{III}>\pi_R^{II}=\pi_M^{III}$;

②Under Semi-cooperative Decision-making:

$\pi_M^{VII}=\pi_R^{VII}>\pi_M^{VI}=\pi_R^{V}$, $\pi_M^{V}=\pi_R^{VI}>\pi_R^{V}=\pi_M^{VI}$.

(2) Comparison of total profits of supply chain systems.

① Under Non-cooperative Decision-making : $\pi_J^{IV}>\pi_J^{II}=\pi_J^{III}$;

②Under Semi-cooperative Decision-making: $\pi_J^{VII}>\pi_J^{V}=\pi_J^{VI}$;

③The profit level of the system under cooperative decision is the highest, that is, $\pi_J^{I}>\pi_J^{VII}>\pi_J^{IV}$.

Proof: It can be known from $b\eta>k^2$

(1)Under Non-cooperative Decision-making

$$\pi_M^{IV}-\pi_M^{III}=\pi_R^{IV}-\pi_R^{II}=\frac{\eta(9b\eta-2k^2)(a-bc)^2}{(9b\eta-4k^2)^2}-\frac{\eta(8b\eta-k^2)(a-bc)^2}{2(8b\eta-3k^2)^2}=\frac{b^2\eta^2(504b\eta-463k^2)+k^4(154b\eta-20k^2)}{2(8b\eta-3k^2)^2(9b\eta-4k^2)^2/\eta(a-bc)^2}>0$$

$$\pi_M^{II}-\pi_M^{III}=\pi_R^{III}-\pi_R^{II}=\frac{2\eta(4b\eta-k^2)(a-bc)^2}{(8b\eta-3k^2)^2}-\frac{\eta(8b\eta-k^2)(a-bc)^2}{2(8b\eta-3k^2)^2}=\frac{\eta(a-bc)^2}{2(8b\eta-3k^2)}>0$$ hold true;

Under Semi-cooperative Decision-making

$$\pi_M^{VII}-\pi_M^{VI}=\pi_R^{VII}-\pi_R^{V}=\frac{\eta(a-bc)^2}{9b\eta-8k^2}-\frac{\eta(8b\eta-9k^2)(a-bc)^2}{8(4b\eta-3k^2)^2}=\frac{b\eta^2(a-bc)^2(56b\eta-47k^2)}{8(4b\eta-3k^2)^2(9b\eta-8k^2)}>0,$$

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$\pi_M^V - \pi_M^{VI} = \pi_R^{VI} - \pi_R^V = \dfrac{b\eta^2(a-bc)^2}{(4b\eta-3k^2)^2} > 0$ hold true.

(2) As to the Profit Comparison for Supply Chain Systems

① For $\pi_J^{IV} - \pi_J^{II} = \dfrac{b^2\eta^2(360b\eta-107k^2)-k^4(36b\eta-8k^2)}{2(9b\eta-4k^2)^2(8b\eta-3k^2)^2/\eta(a-bc)^2}$.

From $b\eta > k^2$, it knows that $b^2\eta^2(360b\eta-107k^2) > k^4(360b\eta-107k^2)$, therefore

$$\pi_J^{IV} - \pi_J^{II} = \frac{\eta k^4(a-bc)^2(324b\eta-99k^2)}{2(9b\eta-4k^2)^2(8b\eta-3k^2)^2} > 0;$$

② $\pi_J^{VII} - \pi_J^V = \dfrac{5b\eta^2(a-bc)^2}{4(9b\eta-8k^2)(4b\eta-3k^2)} > 0$ hold true;

③ $\pi_J^I - \pi_J^{VII} = \dfrac{b\eta^2(a-bc)^2}{4(b\eta-k^2)(9b\eta-8k^2)} > 0$, $\pi_J^{VII} - \pi_J^{IV} = \dfrac{36b\eta^2k^2(a-bc)^2}{(9b\eta-8k^2)(9b\eta-4k^2)^2} > 0$.

Hence $\pi_J^I > \pi_J^{VII} > \pi_J^{IV}$ hold true.

From Theorem 5.3, it can be seen that whether it is non-cooperative or semi-cooperative decision-making, the two sides of the game are still in a situation that the one who dominates is the one who prevails over, which is consistent with the previous results. However, the profit of the supply chain system is not affected by the power structure, and when the two sides are equal, the profit of the upstream and downstream enterprises is the largest, and the profit of the supply chain system also reaches the optimal level. In addition, it can also be found that the higher the degree of cooperation between the two sides, the higher the profit of the supply chain system. Combined with Theorem 4.2, it can also be seen that the higher the degree of cooperation, the more beneficial it is for enterprises to improve the carbon emission reduction of their products. Therefore, upstream and downstream enterprises should strengthen emission reduction cooperation in the process of low carbonization. Only in this way can better emission reduction effects be achieved.

6. Numerical Examples

The effects of different cooperation degrees and power structures on product pricing, carbon emission reduction and corporate profits under the seven models have been discussed earlier. Then it will use numerical examples for further analysis and verification.

Assuming $a = 2000, b = 50, \eta = 5, c = 20$, and combining the given conditions $b\eta - k^2 > 0$, it knows that $k^2 < 250$. If 1 is taken as a step value for k, the influence of low carbon preference level on emission reduction of upstream and downstream enterprises, supply chain system and enterprise profits can be obtained (Figure 4-5).

Through comparing Figure 4 (a) with Figure 4 (b), it can be seen that when the consumer's low-carbon preference level for products increases, the carbon emission reduction under non-cooperative decision-making presents a linear increase. Moreover, the carbon emission reduction of dominant enterprises is significantly higher than that of follower enterprises, while the emission reduction of enterprises under other decision-making models is also distorted upward. Whether upstream or downstream enterprises, the upward distortion of emission reduction is consistent and large. Especially, the higher the degree of cooperation in emission reduction, the stronger the sensitivity to the low-carbon preference of consumers in the terminal market. When the upstream and downstream enterprises have equal status, the emission reduction level under the semi-cooperative decision is second only to the emission reduction level under the complete cooperation, which shows that besides the degree of cooperation, the power structure also has a significant impact on the emission reduction of enterprises.

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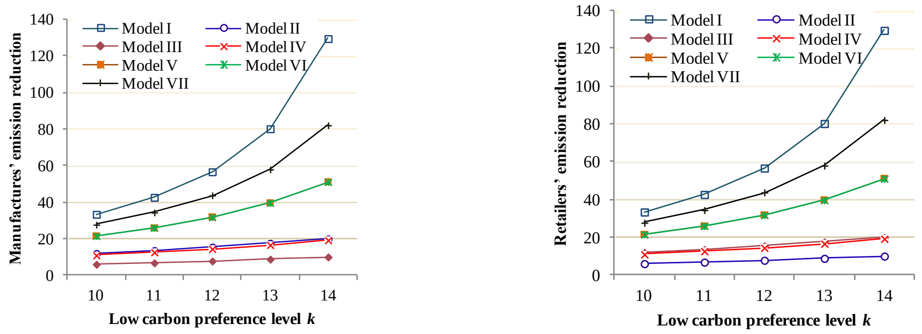
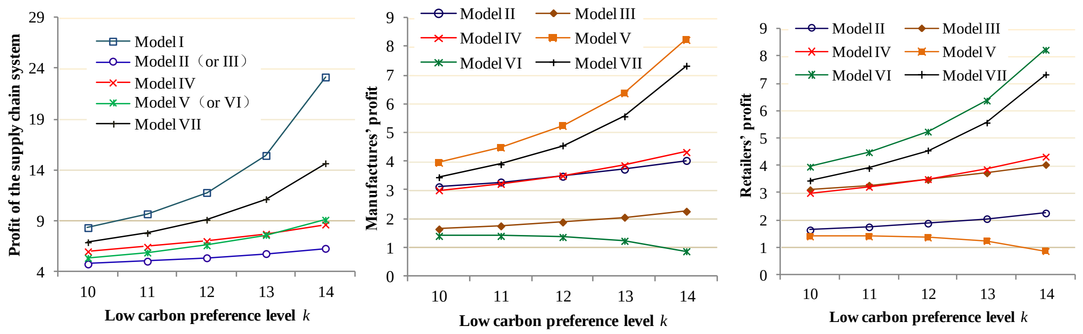


(a) (b)

Figure 4: Influence of low carbon preference level on emission reduction.

From Figure 5 (a), it can be seen that consumers' low-carbon preference has a positive impact on the profits of the supply chain system, and complete cooperation among enterprises can realize the profit maximization, followed by semi-cooperation and finally the non-cooperation. Therefore, from the perspective of the whole supply chain, strengthening the degree of cooperation among enterprises in emission reduction is conducive to the supply chain to obtain higher profits. Then combined with Figure 5 (b) and Figure 5 (c), in addition to the degree of inter-enterprise cooperation, who is dominant also has a great influence on the profits of enterprises. The next is both are in equal status, and the follower gets the lowest profit. With the increase of low carbon preference level, the profit of the follower enterprises adopting semi-cooperative decision-making will show a downward trend, because carbon emission reduction jointly decided by the upstream and downstream enterprises at this time is low, which results in a lower market demand for products.



(a) (b) (c)

Figure 5: The influence of low carbon preference level on profit ($\times 10^3$).

According to the above assumptions, take $k=10$ and keep the values of other parameters unchanged, then determine the change trend of the corresponding carbon emission reduction and enterprise profits when considering the changes that meet the conditions $b\eta - k^2 > 0$ (see Figure 6-7).

Figure 6 shows that no matter the channel status of upstream and downstream enterprises and the degree of cooperation between them, the impact of the cost coefficient of carbon emission reduction on carbon emission reduction of enterprises is negatively correlated, and with the increase of cost coefficient, the decline degree of carbon emission reduction is relatively large at the beginning, and then it will gradually tend to be flat. To investigate its reason, it is not difficult to understand that the cost of carbon emission reduction does have a direct impact on the emission reduction of enterprises, but under a certain level of low-carbon consumption preference, in order to grasp the demand of market segments, the products must maintain a certain amount of emission reduction. The transmission of this influence will cause the profit level of supply chain system and node enterprises to decline, which can be seen obviously fromFigure7. However, the profits of follower enterprises adopting semi-cooperative decision-making slowly climb and gradually tend to be flat, indicating that the increased cost of carbon emission reduction has little impact on their lower emission reduction. In addition, the higher retail price of independent decision-making has made their low profit level have some room to rise.

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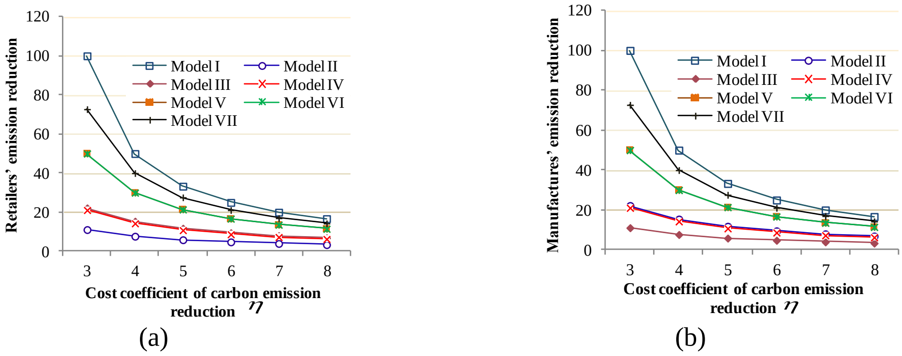

Figure 6: Influence of the cost coefficient carbon emission reduction on emission reduction.

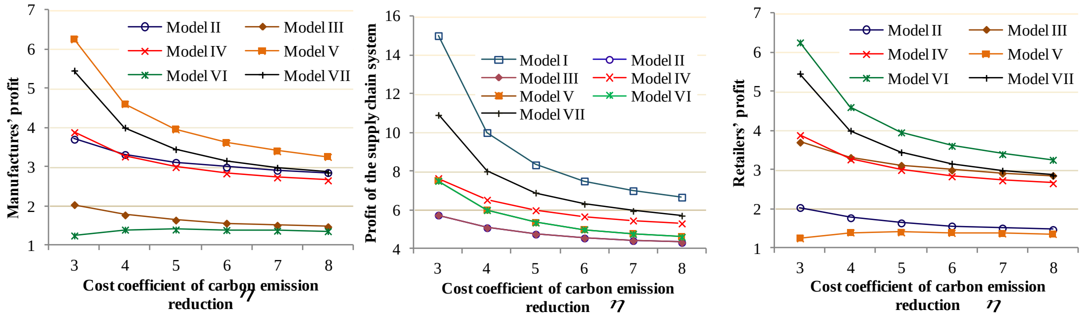

Figure 7: Influence of the cost coefficient of carbon reduction on profit (×10^3).

7. Conclusion

This paper studies the carbon emission reduction and pricing of upstream and downstream enterprises in different dominant positions. As the market demand of products is not only affected by pricing, it is also affected by the low-carbon preference of consumers, so how the emission reduction level of enterprises will directly affect the market demand, and then affect the profits of various enterprises. Therefore, how to give consideration to the low-carbon nature of products and the emission reduction costs, the power structure and cooperation model of enterprises are particularly critical. The research shows that the higher the degree of cooperation between enterprises, the higher the profit of supply chain system, and the more beneficial it is for enterprises to improve the carbon emission reduction of their products. Whether it is non-cooperative or semi-cooperative decision-making, the two sides of the game are still the one who dominates is the one who prevails over. However, if the two sides of the enterprise have equal status at this time, the carbon emission reduction of the product is the largest and it is most conducive to cooperative emission reduction. Therefore, in addition to the degree of enterprise cooperation, the impact of power structure on enterprise emission reduction is also very significant. For consumers, if the product pricing factor is further considered, the equal status of both enterprises is beneficial to consumers under non-cooperative decision-making, but it is not under semi-cooperative decision-making. In addition, the numerical example analysis also shows that the impact of consumers' low-carbon preference on the profit of supply chain system is positive, and the complete cooperation between enterprises can maximize the profit, followed by semi-cooperation and finally the non-cooperation. Generally speaking, it is more beneficial to the whole low-carbon supply chain system to strengthen the cooperation of emission reduction between enterprises with equal status. Further research can consider using coordination means such as supply chain contract to promote complete cooperation between the two sides, or bringing carbon quota, carbon tax and government differentiated subsidies into the same framework for in-depth analysis.

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