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Low-Carbon Supply Chain Operation Decisions and Coordination Strategies Considering the Consumers' Preferences

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Abstract: Implementing the low-carbon transformation strategy has become an inevitable choice for manufacturing enterprises. However, suppliers often overlook the impact of consumers' preferences for low-carbon products (LCPs) on their own low-carbon strategies. Based on this idea, this study uses game theory models to analyze how consumer preferences affect suppliers' decision-making and coordination strategies in low-carbon supply chains (LCSCs). Results show that (1) manufacturers and retailers are more likely to produce and promote LCPs as consumers become more sensitive to carbon emission reduction (CER); (2) manufacturers are less likely to produce LCPs but retailers are more likely to promote them as consumers become more sensitive to promotional rates; and (3) manufacturers are less likely to produce LCPs but retailers are more likely to promote them as consumers become more sensitive to retail prices. This study concludes that consumer preferences play a crucial role in determining suppliers' decisions and coordination strategies in LCSCs.

Keywords: low-carbon supply chain; evolutionary game; Stackelberg game; consumer preferences; operations decision and coordination strategies

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1. Introduction

Rapid economic development has brought about tremendous changes in people's lives, but it has also resulted in the environmental impact known as the "greenhouse effect" [1]. To curb the release of greenhouse gases into the atmosphere, an increasing number of nations are implementing policies to restrict carbon emissions, and the concept of a low-carbon lifestyle is gaining momentum [2,3]. Therefore, there is now universal recognition that preventing the ongoing trend of global warming and promoting a low-carbon economy are crucial goals for all countries worldwide [4].

With the progress of science and technology, as well as the continuous development of the economy and society, market competition has evolved from solely being among individual enterprises to encompass competition among entire supply chains [5]. Furthermore, developing low-carbon supply chain (LCSC) management is now recognized as the only way to foster a low-carbon economy [6]. Simultaneously, due to the intensifying global economic competition, competition among channel structures within supply chains has become increasingly fierce. Thus, choosing an appropriate cooperation mechanism to mitigate competition among supply chains has become a crucial issue [7]. Furthermore, with the growing awareness of environmental protection among consumers, there is an increasing demand for green products. Downstream enterprises, such as retailers, are motivated to promote green supply chains to achieve higher environmental and social goals. This, in turn, encourages upstream enterprises to produce more green products. Additionally, competition among enterprises has shifted from simple price competition to one that considers both price and low-carbon environmental protection.

In fact, in the context where many communities in society emphasize emission reduction and environmental protection, customers are willing to pay a premium for low-carbon products (LCPs). Under this situation, the market structure has shifted from a single supply chain to multiple supply chains, leading to increasingly complex supply chain operation decisions for suppliers [8]. To alleviate market pressure and meet policy requirements, suppliers are continuously striving for carbon emission reduction (CER) [9]. Their approach to LCPs and marketing encompasses two main aspects. One is that the manufacturers achieve CER from the root by adopting new technologies, new equipment, sewage treatment, and other ways of producing LCPs. The other is that the retailers can promote the production of LCPs by advertising and other means, such as "one degree of electricity per night", "six liters of fuel per hundred kilometers", etc., so as to promote the circulation of LCPs. However, both manufacturers and retailers, as profit-oriented entities, also consider profitability and profit levels as the criteria when determining whether to take action in response to low-carbon policies [10]. For instance, if the production of LCPs and related marketing strategies do not align with the interests of manufacturers and retailers, they may prioritize pursuing higher profits rather than investing low-carbon transformation. Similarly, if the price of LCPs is too high, consumers may opt for ordinary products instead of choosing LCPs.

Admittedly, it is widely known that manufacturers and retailers are not an interests community. They prefer to pursue their higher profits than the overall supply chain's profits. It is worth mentioning that both parties' strategic decisions will affect the other's profits, and the profits of one party will also increase with the efforts of the other party, which is the so-called free-rider effect [11]. In other words, manufacturers' LCPs will cater to the consumers' conception of environmental protection, and then improve the product sales. Meanwhile, retailers can also enjoy the increased profits brought by the increase in product sales without making any effort. Similarly, the retailers' low-carbon marketing will improve the popularity and sales of products, and the manufacturers will also make a profit from it even if they do not choose LCPs. Thus, it can be seen that the impact of consumers' preferences on LCSC operation decisions is one of main driving forces [12]. Based on this, the following problems have arisen in the operation of LCSC.

(I) How do consumer's demands and preferences for low-carbon products affect the coordination of operational decisions for LCSCs?

(II) What theoretical model can effectively assist the decision-making process to reduce carbon emissions while meeting consumer's demands, so as to enhance the sustainability and efficiency of the supply chain while enhancing the market competitiveness of enterprises?

To address the challenges mentioned above, this study mainly uses game theory to analyze the impact of consumers' preferences on LCSC operation decisions for the suppliers. The theoretical contributions of this study are as follows: (I) This study introduces and analyzes consumer's preferences and their impact on supply chain operational decisions. Unlike the traditional supply chain that often neglects the influence of consumer's demands and preferences, this study places great emphasis on the importance of understanding consumer preferences and incorporates them into the decision-making process for low-carbon supply chain operations. (II) A Stackelberg game model is proposed to obtain the best operational decisions and coordination strategies between balancing consumer preferences and low-carbon goals. It recognizes the vital role consumers play in shaping supply chain dynamics and highlights the need to align operational strategies with consumer preferences to achieve sustainable and efficient outcomes. They offer valuable support for the decision-making and coordination strategies in low-carbon supply chain operations and serve as a solid foundation for academic studies and practical applications in related fields, providing essential references and guidance.

The structure of this study is as follows: In Section 2, we review related literature on LCSC management, coordination, and mathematical modeling applications. Section 3 constructs the Stackelberg game model to obtain the manufacturers and retailers' optimal profits with different strategic combinations for LCSC operations. And an evolutionary game model is presented to analyze the equilibrium strategies of manufacturers and retailers. In Section 4, a numerical example is presented to demonstrate the scientific and rational nature of the model. Conclusions and Discussion are provided in Section 5, and Section 6 presents the limitations for this research, and the further work in future research.

2. Literature Review

This section will provide relevant research on LCSC operation, which includes LCSC management, the coordination of the LCSC, and the application of the mathematical model.

2.1. LCSC Management

The LCSC is a supply chain that integrates the concepts and technologies of green, low-carbon, and environmental protection into traditional supply chains. Research on LCSC management has garnered significant attention from scholars. They have examined LCSC management problems through various lenses, such as government regulation, consumer behaviors, and decision-maker preferences, leading to numerous valuable research accomplishments.

The research on government policies is as follows: Considering environmental laws and regulations, Zu et al. [13] analyzed the CER strategy for a two-layer supply chain based on differential game theory. Drake et al. [14] discussed how CER policies affect enterprises' strategies and found that carbon trading, under market conditions with fluctuating carbon prices, can help enterprises gain higher profits. Bian et al. [15] explored the effects of environmental policies, such as emission reduction subsidies and carbon emission taxes, on a three-tier supply chain.

The study concluded that subsidy policies provide greater incentives for manufacturers to reduce pollution, resulting in increased profits for all channel members. However, in cases where emission reduction costs are high and production emissions have severe environmental impacts, tax policies should be implemented instead. Similarly, Zhang et al. [16] observed that carbon tax mechanisms effectively encourage enterprises to lower their carbon emissions. By employing these policies, supply chains can reduce redundancies and promote sustainable practices that benefit all participants involved. Ding et al. [17] investigated the impact of carbon taxes and found that, in some cases, government-introduced carbon taxes may not motivate remanufacturers to control carbon emissions. Xu et al. [18] examined the use of revenue-sharing contracts and two-part tariff contracts to achieve mutual benefits for supplier-led supply chain members while addressing challenges related to carbon emission constraints and trade laws and regulations. It aimed to minimize redundancy within the supply chain by implementing innovative contract mechanisms that ensure fairness, sustainability, and desirable outcomes for all parties involved.

The research on consumer or decision-maker preferences is as follows: Du et al. [19] highlighted the impact of consumers' low-carbon preferences on LCSC operations and revealed the mechanism of consumers' low-carbon preference on the enterprises' CER and profits. Tong et al. [20] also discussed the effect of carbon emission limits and transactions on consumers' preferences for LCPs and analyzed the operational strategies within a retailer-led supply chain. Considering government subsidies and retailers' preference for fairness, Zhang et al. [21] investigated pricing issues in the context of green supply chain operations. In addition, Dong et al. [22] analyzed and compared the profits generated by manufacturers and retailers through individual or simultaneous investments in improving green production. Zhong et al. [23] conducted a study focusing on optimal decisions for an LCSC consisting of a leading manufacturer and a leading retailer, considering green investment and member firms' preferences for fairness. The research aimed to reduce redundancy in supply chains while addressing environmental concerns and stakeholders' expectations of fairness. It is evident that existing research primarily focuses on the impact of consumer preferences on LCSC operational decisions, CER efforts, and enterprise profits. However, there is limited research that investigates how consumers' preferences affect LCP production and sales behaviors of manufacturers and retailers. Based on these findings, this study will examine the game relationship between the decision of whether manufacturers produce LCPs and whether retailers market LCPs. The main factors influencing LCSC operations will be the consumers' sensitivity to retail prices, environmental protection, and promotional activities.

2.2. The Coordination of the LCSC

Supply chain coordination is a crucial concern in supply chain operations. Given that individual members within the supply chain often prioritize maximizing their own profits, they tend to overlook the profits of others [24], the purpose of supply chain coordination is that the members' optimal decisions are consistent with the overall optimal decisions of the supply chain, and it is achieved on the premise of ensuring the interests of members in the supply chain.

In terms of supply chain coordination, Dai [25] investigated the optimal joint strategy using the CVAR method and discovered that the supply chain can be effectively coordinated when the retailer is risk neutral. However, if the retailer has a risk-averse tendency, achieving coordination becomes challenging. Hu et al. [26] discussed coordination within a retailer-led supply chain and highlighted that it can be attained through the design of appropriate contracts. Cachon [27] identified five common contracts and concluded that revenue sharing contracts can achieve coordination in supply chains without involving promotion or pricing behavior. Ghosh and Shahet [28] examined the coordination of a manufacturer-led green supply chain, analyzing the influence of contract parameters on operational decisions by implementing a cost-sharing contract. Zhou et al. [29] confirmed the effectiveness of cooperative advertising contracts and emission reduction cost-sharing contracts in achieving coordination within manufacturer-led LCSCs. By analyzing joint decision-making (DM) and emission reduction strategies, Zhou and Ye [30] explored coordination in dual-channel supply chains using a different game model. Their findings suggested that under certain conditions, cooperative advertising and emission reduction cost-sharing contracts are more efficient than solely using cooperative advertising contracts. Chen et al. [31] discussed the coordination between a dual supply chain and a retailer with a focus on fair commitment to low-carbon efforts, pointing out that coordination can be achieved through a revenue-sharing contract and a cost-sharing mechanism for low-carbon efforts.

Based on the statement above, existing research primarily focuses on achieving coordination within an LCSC by establishing cost-sharing contracts or mechanisms to distribute the costs of low-carbon efforts. However, there has been little attention given to coordinating the LCSC based on the optimal profits for all stakeholders. Therefore, this study aims to fill this gap by first determining the manufacturers' and retailers' optimal profits under different strategy combinations, and subsequently achieving coordination within the LCSC based on these findings.

2.3. Application of Evolutionary Game Model

The game model plays an important role in the application of the LCSC with its unique advantages, and the research on the LCSC management in different situations has been solved by it.

Using game theory, under the background of carbon quota and carbon trading, Xu et al. [32] discussed the impact mechanism of implementing CER policies on the enterprises' CER and economic and social benefits. Yao et al. [33] investigated the coordination of the LCSC by applying the difference game theory, which showed that the manufacturers always prefer to adopt coordination mechanisms, since the manufacturers and retailers always make a profit when the manufacturers adopt the cost sharing plans. Based on the constructed Nash and Stackelberg game models, Zhang et al. [34] explored the optimal retail price, manufacturers' profits, and the degree of carbon dioxide emission reduction. Zakeri et al. [35] investigated the operation decisions of supply chain members under carbon tax by proposing a supply chain planning model. Yenipazarli [36] constructed the Stackelberg game model and studied the impact of carbon tax and carbon trading regulation on the producers' decisions. Luo et al. [37] developed four game theory models to investigate how carbon tax policies impact manufacturing and remanufacturing decisions within closed-loop supply chains, and the results showed that the manufacturers were reluctant to reduce emissions from remanufacturing. Zhong et al. [23] constructed four Stackelberg game decision models to investigate the LCSC operation decision composed of manufacturers and retailers. Drake et al. [14] used a stochastic model to examine the impact of enterprise capacity decisions under a comprehensive control and trading system. They found that expected profits and total carbon emissions are higher under the comprehensive control and trading system than under the carbon emission tax mode.

From the existing research, the manufacturers' and retailers' strategic selection behaviors depend on the choice of the other's behavior, and their interests also change in the process of LCSC operation. Therefore, this study will adopt the evolutionary game theory to analyze the long-term dynamic game between the manufacturers' and retailers' behaviors.

In summary, to describe the existing research more clearly, a table is created which includes the research objective, methodology, and the research perspective of existing literature. However, due to space limitations, only a portion of the literature is shown in Table 1.

Table 1. The summary of the relevant literature.

No.	Research Objective	Methodology	Research Perspective	References
1	Low-carbon behavior strategies for supply chain enterprises.	Evolutionary game theory and Stackelberg game theory	Carbon allowance	[9,18,38]
2	Investment in low-carbon technology and carbon emission reduction for supply chain enterprises.	Optimization theory	Government subsidies	[9,15,39]
3	Optimization and pricing of supply chain.	Stackelberg game theory and optimization theory	Competition and environmental awareness for all stakeholders	[32,40–42]
4	Consumers' recognition and selection for low-carbon products.	Differential game theory	Consumers' low-carbon preferences	[12,39,43,44]
5	Low-carbon supply chain operation decisions and coordination strategies.	Evolutionary game theory	Consumers' preferences	This paper

3. Methodology

For the convenience of the description, the manufacturers and the retailers are referred to as suppliers in this study, and the manufacturers' production behaviors and the retailers' marketing behaviors are referred to as the production and marketing behaviors, where the manufacturers' LCPs are referred to as the LCPs. This section will state the research framework of methods in this study including the Stackelberg game and evolutionary game.

3.1. Stackelberg Equilibrium Strategies for LCSC Operations

This subsection will give the research procedure of the Stackelberg game including descriptions of problem and symbols, basic assumptions and construction and solving of the game model.

3.1.1. Descriptions of Problem and Symbols

When manufacturers produce and utilize goods, a certain amount of polluting gas that harms the environment is generated. As people are increasingly environmentally conscious, consumers tend to choose goods with lower levels of pollution. Moreover, the government has also issued a large number of carbon tax policies to limit the carbon emissions of enterprises. For manufacturers and retailers, carbon emissions not only contribute to environmental pollution but also lead to profit loss. CER has become a critical factor directly affecting the profits of various stakeholders within the supply chain. Therefore, during the production and marketing processes, both manufacturers and retailers must consider the impact of LCPs and marketing strategies on their profits while maintaining their regular operational strategies.

In this section, we consider the impact of consumer sensitivity to retail prices, environmental and promotional levels, and carbon tax policies on the profits of manufacturers and retailers. To facilitate the discussion, we focus on a single manufacturer and a single retailer within the LCSC. Specifically, we examine the game relationship between the manufacturer's production of LCPs and the retailer's marketing of LCPs. Both manufacturers and retailers in the LCSC act as decision makers and aim to maximize their profits. As manufacturers and retailers are not entirely rational, their decisions are assumed to prioritize current optimality, and both parties constantly adjust their strategies to achieve higher profits. Through continuous strategy adjustments, a fixed strategy combination will eventually be adopted by both sides.

For the convenience of discussion, the following does not consider strategies that have nothing to do with low carbon, such as manufacturers' reducing production costs, retailers' expanding store size, layoffs, and so on. Additionally, manufacturers can decide whether to produce LCPs, and retailers can decide whether to conduct low-carbon marketing only after manufacturers choose to produce LCPs. Otherwise, if the manufacturers do not choose to produce LCPs, the retailers will be assumed to have no choice at all or can only choose non-low-carbon marketing. In actuality, the retailers' marketing and the manufacturers' production are independent, the retailers can market the non-LCPs produced by the manufacturers as well. To summarize, the strategies selected by the manufacturers are the production of LCPs and production of non-LCPs, and those by the retailer are: the marketing of LCPs and the marketing of non-LCPs. Additionally, all notations used to construct the model and their descriptions are shown in Table 2.

Table 2. The symbols and their descriptions.

Symbol	Interpretation of Symbols	Symbol	Interpretation of Symbols
ω	The wholesale price per commodity	u	The profit per commodity
x	The emission reduction rate achieved by LCPs	y	The promotion rate achieved by marketing goods
$p = \omega + u$	The retail price per unit merchandise	b	The consumers' sensitivity coefficient to the retail prices from the retailers (SCRP)
o	The production cost per unit product	c	The consumers' sensitivity coefficient to the carbon reduction rate from the manufacturers (SCCRR)
e	The carbon emissions from non-LCPs	d	The consumers' sensitivity coefficient to the promotion rate from the retailers (SCPR)
k	The cost coefficient of the emission reduction	a	The market capacity
g	The cost coefficient of the marketing	q	The consumer demand
h	The carbon tax rate	/	/

3.1.2. Basic Assumptions of the Model

For convenience in the discussion of the model, we make the following assumptions:

Assumption 1. *Assume that the strategic choices of manufacturers are: LCPs* (M_1) *and non-LCPs* (M_2)*, and their probabilities are:* p_m *and* $1 - p_m$*;*

Assumption 2. *Assume that the strategic choices of retailers are: marketing of LCPs* (R_1) *and marketing of non-LCPs* (R_2)*, and their probabilities are:* p_r *and* $1 - p_r$*;*

Assumption 3. *Assume that consumer behavior is only affected by the commodity retail price, the degree of low-carbon and pro-environmental, and the promotion strength from retailers. Furthermore, consumer demand satisfies the following linear relationship [19]:*

$$q = a - bp + cx + dy$$

where q, p, x, and y are consumer demand, commodity retail price, carbon reduction rate produced by manufacturer, and promotion rate marketed by retailers, and a, b, c, and d are market size, the sensitivity coefficient on promotion rate marketed by retailers for consumers, the sensitivity coefficient on carbon reduction rate produced by manufacturers for consumers, and the sensitivity coefficient on promotion rate marketed by retailers for consumers.

The following assumption references related research [28,45–47] that considers manufacturers' cost to achieve CER to be a concave function of the carbon reduction rate, which implies that the greater carbon reduction, the greater the cost required to achieve CER by manufacturers. Therefore, the assumption is stated as follows:

Assumption 4. *If the carbon reduction rate produced by manufacturers is x, then the cost for manufacturers to achieve CER is*

$$C(x) = \frac{1}{2}kx^2$$

where $k > 0$ is the carbon emissions coefficient.

Similarly, the assumption for the retailers' marketing cost is stated as follows:

Assumption 5. *If the promotion rate marketed by retailers is y, then the marketing cost for retailers is*

$$C(y) = \frac{1}{2}gy^2$$

where $g > 0$ is the marketing cost coefficient.

Assumption 6. *Assume that the unit production cost $o \geq 0$ of a commodity produced by manufacturers is constant, which only affects the profits of both sides and does not affect the strategic choices of both parties and final results, and it can be assumed that $o = 0$.*

Assumption 7. *Assume that the carbon tax paid by manufacturers is he, where e and h denote carbon emission and carbon tax rate, respectively. Furthermore, only the impact of the carbon tax rate, h, on the supply chain is considered and the carbon emission, e, is seen as constant.*

3.1.3. Construction and Solving of the Profit Models for the Suppliers

According to the assumptions mentioned above, it can be easily seen that the strategy combination sets from manufacturers and retailers are (M_1, R_1), (M_1, R_2), (M_2, R_1), and (M_2, R_2). Due to limitations of space, this section will only state the construction and solving of the model for the strategy combination set (M_1, R_1), as other strategy combination sets are similar.

From the above analysis, we can derive the profit functions for both manufacturers and retailers:

$$\pi_M = (w - o)q - \frac{1}{2}kx^2 - heq(1 - x) \tag{1}$$

and

$$\pi_R = uq - \frac{1}{2}gy^2 \tag{2}$$

If $o = 0$, then the following equations are given:

$$\pi_M = wq - \frac{1}{2}kx^2 - heq(1 - x) \tag{3}$$

and

$$\pi_R = uq - \frac{1}{2}gy^2 \tag{4}$$

Since every commodity experiences a process including production, wholesale, and retail in turn, it should be assumed that manufacturers can make the first decisions in the game. Thus, the manufacturers first give the commodity wholesale price w and carbon reduction rate x, and then retailers determine the commodity retail price p and achievable promotion rate y after the strategies of manufacturers are known. Therefore, the optimal solutions of the profit functions can be obtained by inverse deduction. That is, the adopted strategies by the last decision participant will be solved.

Therefore, in a case where manufacturers and retailers select LCPs and marketing LCPs, respectively, in the last stage of the game, the retailer is the player, and its optimal profit function can be expressed as follows:

$$\begin{cases} \pi_R = u[a - b(w+u) + cx + dy] - \frac{1}{2}gy^2 \\ 0 < u < a/b - w, 0 < y < 1 \end{cases} \tag{5}$$

The first-order, partial derivatives with respect to u and y in Equation (5) can be obtained as follows:

$$\begin{cases} \partial\pi_R/\partial u = a - bw - 2bu + cx + dy = 0 \\ \partial\pi_R/\partial y = du - gy = 0 \end{cases} \tag{6}$$

and the Hessian matrix obtained by the second-order, partial derivatives with respect to u and y is

$$\begin{pmatrix} \partial^2\pi_R/\partial u^2 & \partial^2\pi_R/\partial u\partial y \\ \partial^2\pi_R/\partial y\partial u & \partial^2\pi_R/\partial y^2 \end{pmatrix} = \begin{pmatrix} -2b & d \\ d & -g \end{pmatrix}$$

When $d^2 - 2bg < 0$, retailers' profits could be maximized when appropriate profit per unit commodity u and promotion rate y are chosen. Thus, the appropriate u and y are obtained by solving Equation (6) as follows:

$$\begin{cases} \overline{u} = \frac{g(a-bw+cx)}{2bg-d^2} \\ \overline{y} = \frac{d(a-bw+cx)}{2bg-d^2} \end{cases} \tag{7}$$

Based on the above determined optimal results, the optimal manufacturers' profits can be derived with a recursive method. Then, the optimal profits function for manufacturers is expressed as follows:

$$\begin{cases} \pi_M = [w - he(1-x)][a - b(w+u) + cx + dy] - \frac{1}{2}kx^2 \\ 0 < w < a/b - u, 0 < x < 1 \end{cases} \tag{8}$$

where $u = \overline{u} = \frac{g(a-bw+cx)}{2bg-d^2}$, $y = \overline{y} = \frac{d(a-bw+cx)}{2bg-d^2}$.

Using a similar procedure to that of obtaining retailers' optimal profits, first-order conditions of profits function for manufacturers are as follows:

$$\begin{cases} \partial\pi_M/\partial w = \frac{bg[(c-bhe)x - 2bw + a + bhe]}{2bg-d^2} = 0 \\ \partial\pi_M/\partial x = \frac{bg((c-bhe)w) + \left[k\left(d^2-2bg\right) + 2cbheg\right]x + (a-c)bheg}{2bg-d^2} = 0 \end{cases} \tag{9}$$

and the Hessian matrix is

$$\begin{pmatrix} \partial^2\pi_M/\partial w^2 & \partial^2\pi_M/\partial w\partial x \\ \partial^2\pi_M/\partial x\partial w & \partial^2\pi_M/\partial x^2 \end{pmatrix} = \begin{pmatrix} 2b^2g/\left(d^2-2bg\right) & bg(bhe-c)/\left(d^2-2bg\right) \\ bg(bhe-c)/\left(d^2-2bg\right) & \left[2bg(k-che) - d^2k\right]/\left(d^2-2bg\right) \end{pmatrix}$$

When $2k\left(d^2-2bg\right)+g(c+bhe)^2<0$, the Hessian matrix is negative. Therefore, there are optimal values for the wholesale price and emission reduction rate that maximize the manufacturer's profit. By solving Equation (9), the optimal w^* and x^* can be obtained as follows:

$$w^*=\frac{bhe\left[k\left(2bg-d^2\right)-cg(c+bhe)\right]+a\left[k\left(2bg-d^2\right)-bheg(c+bhe)\right]}{b\left[2k\left(2bg-d^2\right)-g(c+bhe)^2\right]}$$

and

$$x^*=\frac{g(c+bhe)(a-bhe)}{2k\left(2bg-d^2\right)-g(c+bhe)^2}$$

Then, the optimal u^* and y^* are calculated by substituting w^* and x^* into Equation (7) as follows:

$$u^*=\frac{kg(a-bhe)}{2k\left(2bg-d^2\right)-g(c+bhe)^2}$$

and

$$y^*=\frac{hd(a-bhe)}{2k\left(2bg-d^2\right)-g(c+bhe)^2}$$

Thus, the optimal value, p^*, is

$$p^*=\frac{k\left(2bg-d^2\right)(bhe+a)-gbhe(c+bhe)(c+a)+bkg(a-bhe)}{b\left[2k\left(2bg-d^2\right)-g(c+bhe)^2\right]} \tag{10}$$

Finally, substituting u^*, y^*, w^*, and x^* into Equation (1) and combining Assumption 5, we can obtain the optimal profits for both manufacturers and retailers using the following expressions:

$$\begin{cases}\pi_M^*=\frac{kg(a-bhe)^2}{2\left[2k\left(2bg-d^2\right)-g(c+bhe)^2\right]}\\ \pi_R^*=\frac{k^2g\left(2bg-d^2\right)(a-bhe)^2}{2\left[2k\left(2bg-d^2\right)-g(c+bhe)^2\right]^2}\end{cases} \tag{11}$$

At this point, we can obtain the optimal profit functions for both sides of the game under the strategy combination set (M_1,R_1). The methods of constructing and solving models under other strategy combination sets are all the same, so they will not be described in detail here. Table 3 presents the optimal profits for manufacturers and retailers under each strategy combination set.

Table 3. The optimal profits of manufacturers and retailers under each strategy combination set.

Strategy Combination Sets	π_M^*	π_R^*
(M_1,R_1)	$\frac{kg(a-bhe)^2}{2\left[2k\left(2bg-d^2\right)-g(c+bhe)^2\right]}$	$\frac{k^2g\left(2bg-d^2\right)(a-bhe)^2}{2\left[2k\left(2bg-d^2\right)-g(c+bhe)^2\right]^2}$
(M_1,R_2)	$\frac{k(a-bhe)^2}{2\left[4bk-(c+bhe)^2\right]}$	$\frac{bk^2(a-bhe)^2}{\left[4bk-g(c+bhe)^2\right]^2}$
(M_2,R_1)	$\frac{g(a-bhe)^2}{4\left(2bg-d^2\right)}$	$\frac{g(a-bhe)^2}{8\left(2bg-d^2\right)}$
(M_2,R_2)	$\frac{(a-bhe)^2}{8b}$	$\frac{(a-bhe)^2}{16b}$

3.2. Evolutionary Game Modeling Analysis

The copying dynamic equation is derived from the principle that within a group of game players with limited rationality, strategies that yield superior outcomes than the average will gradually be adopted by a greater number of players. Consequently, there will be a shift in the proportion of players utilizing different strategies within the group. In this section, an evolutionary game model will be constructed using replication dynamic equations, which illustrate the changes in profits for manufacturers and retailers under various scenarios of strategy selection.

3.2.1. Model Construction and Equilibrium Solution Solving

If the profits under different strategy combination sets for manufacturers and retailers are denoted as $\left(\pi_{M_1}^{R_1}, \pi_{R_1}^{M_1}\right)$, $\left(\pi_{M_1}^{R_2}, \pi_{R_2}^{M_1}\right)$, $\left(\pi_{M_2}^{R_1}, \pi_{R_1}^{M_2}\right)$, and $\left(\pi_{M_2}^{R_2}, \pi_{R_2}^{M_2}\right)$, then, from Table 3, we construct the profit matrix for manufacturers and retailers under each strategy combination, as shown in Table 4.

Table 4. The profit matrix for manufacturers and retailers.

Manufacturers/Retailers	R_1	R_2
M_1	$\left(\pi_{M_1}^{R_1}, \pi_{R_1}^{M_1}\right)$	$\left(\pi_{M_1}^{R_2}, \pi_{R_2}^{M_1}\right)$
M_2	$\left(\pi_{M_2}^{R_1}, \pi_{R_1}^{M_2}\right)$	$\left(\pi_{M_2}^{R_2}, \pi_{R_2}^{M_2}\right)$

According to Assumptions 1 and 2, the profits for manufacturers selecting low-carbon and non-LCPs are

$$M_L = p_r \pi_{R_1}^{M_1} + (1 - p_r)\pi_{R_2}^{M_1},\ M_{NL} = p_r \pi_{R_1}^{M_2} + (1 - p_r)\pi_{R_2}^{M_2}$$

and the average profit of them is

$$\overline{M} = p_m M_L + (1 - p_m) M_{NL}$$

Thus, we can derive the replication dynamic equation for manufacturers as follows:

$$\begin{aligned} C_M(p_m) &= \tfrac{\mathrm{d}p_m}{\mathrm{d}t} = p_m\left(M_L - \overline{M}\right) = p_m(1 - p_m)(M_L - M_{NL}) \\ &= p_m(1 - p_m)\left(p_r\left(\pi_{R_1}^{M_1} - \pi_{R_1}^{M_2}\right) + (1 - p_r)\left(\pi_{R_2}^{M_1} - \pi_{R_2}^{M_2}\right)\right) \end{aligned} \tag{12}$$

Obviously, if $C_M(p_m) < 0$, then the income of manufacturers from LCPs is low, and increasing the proportion of LCP strategies will reduce profits. Therefore, the manufacturer will reduce the proportion of LCP strategies to increase their profits. Conversely, if $C_M(p_m) < 0$, the manufacturer will increase the proportion of LCP strategies to increase their profits. Additionally, the manufacturer will not change their strategy proportion since the profit is not $C_M(p_m) = 0$.

Similarly, the profits for retailers' marketing of LCPs and non-LCPs are

$$R_L = p_m \pi_{M_1}^{R_1} + (1 - p_m)\pi_{M_2}^{R_1}$$

$$R_{NL} = p_m \pi_{M_1}^{R_2} + (1 - p_m)\pi_{M_2}^{R_2}$$

and the average profit of them is

$$\overline{R} = p_r R_L + (1 - p_r) R_{NL}$$

Thus, we can derive the replication dynamic equation for retailers as follows:

$$\begin{aligned} C_R(p_r) &= \tfrac{\mathrm{d}p_r}{\mathrm{d}t} = p_r\left(R_L - \overline{R}\right) = p_r(1 - p_r)(R_L - R_{NL}) \\ &= p_r(1 - p_r)\left(p_m\left(\pi_{M_1}^{R_1} - \pi_{M_1}^{R_2}\right) + (1 - p_m)\left(\pi_{M_2}^{R_1} - \pi_{M_2}^{R_2}\right)\right). \end{aligned} \tag{13}$$

A similar statement for retailers' replication dynamic equation is presented, and it is not repeated here.

Finally, combining the replication dynamic Equations (12) and (13), a two-dimensional replication dynamic system using p_m and p_r as the variables, for the evolutionary game, is obtained as follows:

$$\begin{cases} C_M(p_m) = p_m(1-p_m)\left(p_r\left(\pi_{R_1}^{M_1} - \pi_{R_1}^{M_2}\right) + (1-p_r)\left(\pi_{R_2}^{M_1} - \pi_{R_2}^{M_2}\right)\right) \\ C_R(p_r) = p_r(1-p_r)\left(p_m\left(\pi_{M_1}^{R_1} - \pi_{M_1}^{R_2}\right) + (1-p_m)\left(\pi_{M_2}^{R_1} - \pi_{M_2}^{R_2}\right)\right) \end{cases} \tag{14}$$

When $C_M(p_m) = 0$ and $C_R(p_r) = 0$, five strategy equilibrium points of Equation (14) can be calculated, and the analysis reveals that there are four pure strategy equilibrium points and one mixed strategy equilibrium point. The five points are $E_1(0,0)$, $E_2(0,1)$, $E_3(1,0)$, $E_4(1,1)$, and $E_5(p_m^*, p_r^*) \in (0,1)$, and

$$p_m^* = \frac{\pi_{M_2}^{R_2} - \pi_{M_2}^{R_1}}{\pi_{M_1}^{R_1} - \pi_{M_1}^{R_2} - \pi_{M_2}^{R_1} + \pi_{M_2}^{R_2}}, p_r^* = \frac{\pi_{R_2}^{M_2} - \pi_{R_2}^{M_1}}{\pi_{R_1}^{M_1} - \pi_{R_1}^{M_2} - \pi_{R_2}^{M_1} + \pi_{R_2}^{M_2}}.$$

Lyapunov [48] stated that a point can be an asymptotically stable equilibrium point only if it meets pure strategy Nash equilibrium. The Jacobian matrix of the system is derived from Equation (14):

$$\begin{pmatrix} \frac{\partial C_M(p_m)}{\partial p_m} & \frac{\partial C_M(p_m)}{\partial p_r} \\ \frac{\partial C_R(p_r)}{\partial p_m} & \frac{\partial C_R(p_r)}{\partial p_r} \end{pmatrix} = \begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix} \tag{15}$$

$$J_{11} = (1-2p_m)\left(p_r\left(\pi_{R_1}^{M_1} - \pi_{R_1}^{M_2}\right) + (1-p_r)\left(\pi_{R_2}^{M_1} - \pi_{R_2}^{M_2}\right)\right);$$
$$J_{12} = p_m(1-p_m)\left(\pi_{R_1}^{M_1} - \pi_{R_1}^{M_2} - \pi_{R_2}^{M_1} + \pi_{R_2}^{M_2}\right);$$
$$J_{21} = p_r(1-p_r)\left(\pi_{M_1}^{R_1} - \pi_{M_1}^{R_2} - \pi_{M_2}^{R_1} + \pi_{M_2}^{R_2}\right);$$
$$J_{22} = (1-2p_r)\left(p_m\left(\pi_{M_1}^{R_1} - \pi_{M_1}^{R_2}\right) + (1-p_m)\left(\pi_{M_2}^{R_1} - \pi_{M_2}^{R_2}\right)\right)$$

When $J_{11} + J_{22} < 0$ and $\begin{vmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{vmatrix} = J_{11}J_{22} - J_{12}J_{21} > 0$, the evolutionary equilibrium points of the system are its stable points, and these two conditions are indispensable.

Obviously, the evolutionary equilibrium point (p_m^*, p_r^*) is not a stable point of the system, since $J_{11} + J_{22} = 0$ at this point. Additionally, any point related to p_m^* or p_r^*, such as $(p_m^*, 0)$, $(p_m^*, 1)$, $(0, p_r^*)$, or $(1, p_r^*)$, is not a stable point of system. Therefore, the other four points $E_1(0,0)$, $E_2(0,1)$, $E_3(1,0)$, and $E_4(1,1)$ are possible stable points, and whether they are stable points depends on some relevant parameters corresponding to manufacturers and retailers' profits. The evolutionary stability conditions at every equilibrium point are shown in Table 5.

Table 5. The evolutionary stability conditions at every equilibrium point.

Equilibrium Points	J_{11}	J_{12}	J_{21}	J_{22}	Conditions
$E_1(0,0)$	$\pi_{R_2}^{M_1} - \pi_{R_2}^{M_2}$	0	0	$\pi_{M_2}^{R_1} - \pi_{M_2}^{R_2}$	$4bk - (c+bhe)^2 < 0$ $8(2bg - d^2) < 0$
$E_2(0,1)$	$\pi_{R_1}^{M_1} - \pi_{R_1}^{M_2}$	0	0	$\pi_{M_2}^{R_2} - \pi_{M_2}^{R_1}$	$2k(2bg - d^2) - g(c+bhe)^2 < 0$ $8(2bg - d^2) > 0$
$E_3(1,0)$	$\pi_{R_2}^{M_2} - \pi_{R_2}^{M_1}$	0	0	$\pi_{M_1}^{R_1} - \pi_{M_1}^{R_2}$	$4bk - (c+bhe)^2 > 0$ $2k(2bg - d^2) - g(c+bhe)^2 < 0$
$E_4(1,1)$	$\pi_{R_1}^{M_2} - \pi_{R_1}^{M_1}$	0	0	$\pi_{M_1}^{R_2} - \pi_{M_1}^{R_1}$	$2k(2bg - d^2) - g(c+bhe)^2 > 0$

3.2.2. The Analysis of System Evolutionary Stability Strategies Considering the Consumers' Preferences

This subsection will analyze the selection of strategies under different situations for manufacturers and retailers by discussing the relationship between evolutionary stability strategies and every variable. Here, the main discussed variables are the emission reduction cost coefficient k, marketing cost coefficient g, carbon tax rate h, sensitivity coefficient, b, of consumers to retail price, sensitivity coefficient, c, of consumers to emission reduction rate, and sensitivity coefficient, d, of consumers to promotion rate.

Combined with the optimal profits under different strategy combinations in Table 3, if the profits obtained from a strategy for manufacturers or retailers are positive, on the premise that all coefficients are positive, then this strategy will be chosen no matter what decision the other party chooses. Conversely, if the profits obtained from a strategy for manufacturers or retailers are negative, on the premise that all coefficients are positive, then this strategy will not be chosen, no matter what decision the other party chooses. Based on this, the simplified conditions for judging different stability strategies of the system are listed in Table 6.

Table 6. The simplified conditions for judging different stability strategies.

Stability Strategies	Conditions	
(M_1, R_1)	$2k(2bg-d^2)-g(c+bhe)^2>0$	$2k(2bg-d^2)-g(c+bhe)^2>0$
(M_1, R_2)	$4bk-(c+bhe)^2>0$	$2k(2bg-d^2)-g(c+bhe)^2<0$
(M_2, R_1)	$2k(2bg-d^2)-g(c+bhe)^2<0$	$8(2bg-d^2)>0$
(M_2, R_2)	$4bk-(c+bhe)^2<0$	$8(2bg-d^2)<0$

Considering the influence of consumers' sensitivity to emission reduction rate, c, and promotion rate, d, on system stability, the results are analyzed as follows:

(1) When $c<\sqrt{2k(2bg-d^2)/g}-bhe$, $d<\sqrt{2bg-g(c+bhe)^2/(2k)}$, the evolutionary stable point of the system is $E(1,1)$, and the phase diagram of system evolution is shown in Figure 1a. It is known that, when consumers have a weak preference for LCPs and promotions, the profits obtained by retailers in marketing goods and manufacturers in LCPs are greater than that of the "free-rider". Under this situation, both the manufacturers and retailers prefer to choose LCPs and promotions behaviors. That is, the evolutionary stability strategy of the LCSC operation system is "manufacturers choose to produce LCPs; retailers choose to market goods".

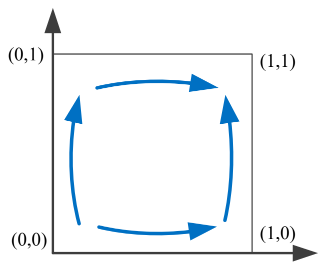
(2) When $c>\sqrt{2k(2bg-d^2)/g}-bhe$, $d<\sqrt{2bg}$, the evolutionary stable point of the system is $E(0,1)$, and the phase diagram of system evolution is shown in Figure 1b. It is known that, when consumers have a strong preference for LCPs and a weak preference for low-carbon promotions, the profits obtained by retailers in marketing goods is larger than that from the free-rider. Additionally, the profits obtained by manufacturers for LCPs is larger than that from non-LCPs (retailers do not choose to market goods) and smaller than that from the free-rider. Under this situation, the manufacturers do not prefer to choose LCPs, and retailers prefer to choose low-carbon promotions. That is, the evolutionary stability strategy of the LCSC operation system is "manufacturers choose to produce non-LCPs; retailers choose to market goods".

(3) When $c<\sqrt{kb}-bhe$, $d>\sqrt{2bg-g(c+bhe)^2/(2k)}$, the evolutionary stable point of the system is $E(1,0)$, and the phase diagram of system evolution is shown in Figure 1c. It is known that, when consumers have a weak preference for LCPs and strong preference for low-carbon promotions, the profits obtained by retailers in marketing goods is larger than that from non-LCPs (manufacturers do not choose to produce LCPs) and is smaller than that from the free-rider, while the profits obtained by manufacturers for LCPs is larger than that from the free-rider. Under this situation, the manufacturers prefer to choose LCPs and retailers do not prefer to choose low-carbon promotions. That is, the evolutionary stability

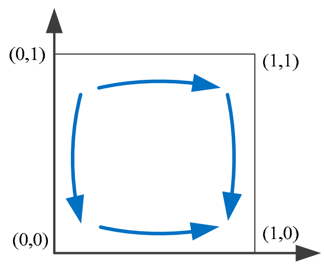
strategy of the LCSC operation system is "manufacturers choose to produce LCPs; retailers choose to market non-LCPs".

(4) When $c > 2\sqrt{kb} - bhe$, $d > \sqrt{2bg}$, the evolutionary stable point of the system is $E(0,0)$, and the phase diagram of system evolution is shown in Figure 1d. It is known that, when consumers have a strong preference for LCPs and promotions, the profits obtained by the retailers in marketing the goods and the manufacturers in producing LCPs is larger than the cost consumed by low-carbon behaviors from manufacturers and retailers. Under this situation, manufacturers and retailers do not prefer to spend money on emission reduction, and the evolutionary stability strategy of the LCSC operation system is: "manufacturers choose to produce non-LCPs; retailers choose to market non-LCPs".

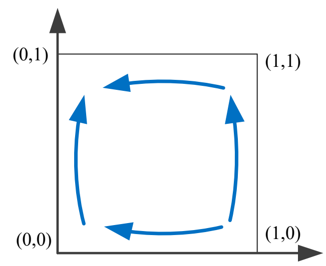
(5) When $\sqrt{2k(2bg - d^2)/g} - bhe < c < 2\sqrt{kb} - bhe$, $\sqrt{2bg - g(c + bhe)^2/(2k)} < d < \sqrt{2bg}$, then the evolutionary stable points of the system are $E(0,1)$ and $E(1,0)$, and the phase diagram of system evolution is shown in Figure 1e. It is known that, when consumers' preference for LCPs and promotion behaviors is within a certain range, the profit increase brought by retailers' marketing goods and manufacturers' LCPs is greater than the consumed cost of low-carbon behaviors (when the other party does not produce and sell LCPs), and it is smaller than the profit obtained by the free-rider. Under this situation, if manufacturers choose to produce non-LCPs, then retailers prefer to market LCPs; and if manufacturers choose to produce LCPs, then retailers prefer to market non-low-carbon promotion. Therefore, the two evolutionary stability strategies of the LCSC operation system are as follows: "manufacturers choose to produce non-LCPs; retailers choose to market low-carbon promotion" and "manufacturers choose to produce LCPs; retailers choose to market non-low-carbon promotion".



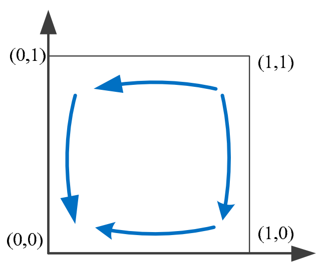
(**a**) The phase diagram of the evolution trend point (1,1)



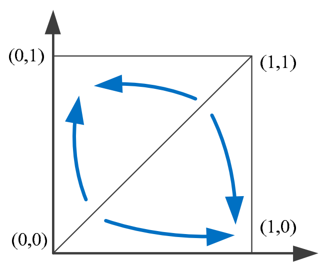
(**b**) The phase diagram of the evolution trend point (1,0)



(**c**) The phase diagram of the evolution trend point (0,1)



(**d**) The phase diagram of the evolution trend point (0,0)



(**e**) The phase diagram of the evolution trend point (1,0) and (0,1)

Figure 1. The figures of evolution trends.

From the above statement, it can be seen that the larger sensitivity coefficient of consumers to emission reduction rate and promotion rate is not necessarily better. Moderately increasing consumers' preference for LCPs and promotion behaviors can improve the profits of the manufacturers and retailers in LCPs and promotion and promote the low-carbon development of the supply chain. Consumers' excessive preference for LCPs and promotion behaviors will not be conducive to the low-carbon promotion evolution of the supply chain. Therefore, it is beneficial to moderately improve consumers' awareness of environmental protection. Excessive improvement of environmental protection awareness of consumers will inhibit the manufacturers' and retailers' enthusiasm to choose non-LCPs and promotions in pursuit of higher profits.

4. Numerical Example

Using the numerical simulation, this section will further analyze the influence of the consumers' preferences on the evolutionary stability of the system.

From the previous analysis, only two strategy combinations for the manufacturers and retailers, such as (M_1, R_2) and (M_2, R_1), are considered here due to space limitations. Additionally, under this situation, the evolution phase diagram of the system is shown in Figure 2. For the convenience of analysis, the region DBOC in Figure 2 is denoted by the probability, P, of the system strategic combination (M_1, R_2) and the probability of the strategic combination (M_2, R_1) is $1 - P$. So, the influence of the consumers' preferences on the evolutionary stability of the system can be described by the changes of the probability, P or $1 - P$, of the strategic combination (M_1, R_2) or (M_2, R_1).

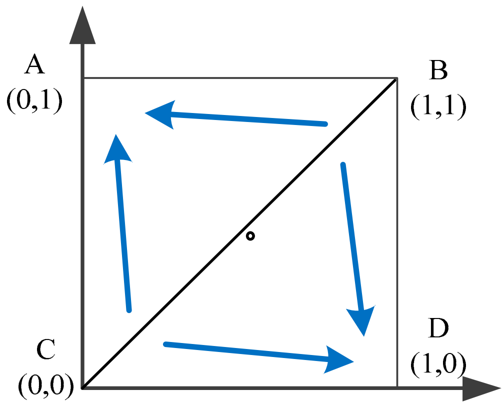


Figure 2. The evolution phase diagram of the system with two strategy combinations.

The implementation procedures of numerical examples are as follows: (I) Determine the variables being analyzed. The influences of the consumers' preferences with the different parameters, such as sensitivity coefficient of consumers to emission reduction rate, promotion rate, and retail price, on the probability will be analyzed. (II) Assigning values to the analyzed variables. According to the related research [12,39] for numerical simulation, the analyzed variables are assigned different values, while other variables are assigned fixed values. For example, when the sensitivity coefficient of consumers to emission reduction rate is analyzed, it is assumed that it varies from 0 to 1, and other variables are assigned to fixed values. (III) Determine the expression of the probability of the system strategic combination. Determining the probability, P, of the system strategic combination is essentially determining the area of region DBOC in Figure 2. Since the area of region DBOC is denoted as $0.5(1 + p_m^* - p_r^*)$, the probability, P, is

$$P = 0.5(1 + p_m^* - p_r^*) = 0.5d^2(4bk - G)\left(d^2(4bk - G)^2 + G\left(2bg - d^2\right)(6bk - G)\right)$$

where $G = (c + bhe)^2$. (IV) Conduct numerical simulation research on the analyzed variables. All variables are assigned values other than the analyzed variable in the expression of the probability, and Matlab software R2016a is used to simulate the trend of the probability changing with the analyzed variable determined in (I).

Next, the influences of all analyzed variables on the probability will be simulated as follows:

(I) The influences of the consumers' sensitivity coefficients to emission reduction rate on the probability

It is assumed that $k = 0.16$, $g = 0.08$, $b = 1$, $h = 0.1$, and $e = 1$ and that these parameters remain constant. The changes of the consumers' sensitivity coefficient, c, to emission reduction rate with the different values of the consumers' sensitivity coefficients to promotion rate, $d = 0.4, 0.35, 0.3, 0.25, 0.2$, are shown in Figure 3. That is, the probability, P, decreases with the consumers' sensitivity coefficients to an increase in emission reduction rate, c, and the downward speed also increases with the increase of the consumers' sensitivity coefficients to promotion rate, d.

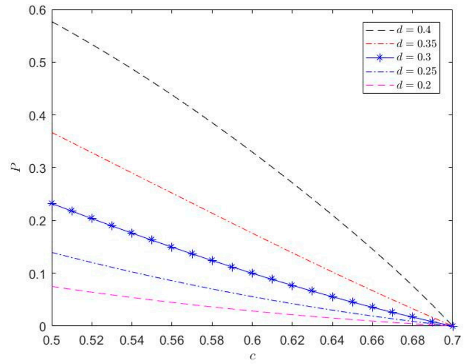


Figure 3. The influence of the consumers' sensitivity coefficients to emission reduction rate on the probability.

It can be seen from Figure 3 that with an increase in the consumers' sensitivity coefficient to CER, there is a decrease in probability.

From Figure 3, it is known that, with the increase in the consumers' sensitivity coefficient to CER, the manufacturers are more likely to produce LCPs. Meanwhile, the stronger the consumers' preference for the low-carbon promotion, the more the retailers will prefer to promote the LCPs.

(II) The influences of the consumers' sensitivity coefficients to promotion rate on the probability

It is assumed that $k = 0.16$, $g = 0.08$, $b = 1$, $h = 0.1$, and $e = 1$ and that these parameters remain constant. The changes of the consumers' sensitivity coefficient, d, to the promotion rate with the different values of the consumers' sensitivity coefficients to promotion rate, $c = 0.6, 0.62, 0.64, 0.66, 0.68$, are shown in Figure 4. It is shown that the probability, P, increases with the consumers' sensitivity coefficients to increases in the promotion rate, d, and the growing speed also increases with the increase in the consumers' sensitivity coefficients to emission reduction rate, c.

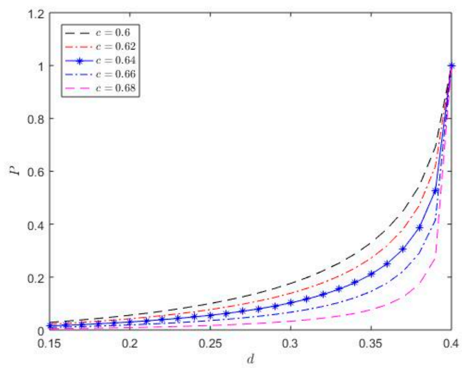


Figure 4. The influence of the consumers' sensitivity coefficients to promotion rate on the probability.

From Figure 4, it is known that, with the increase of the consumers' sensitivity to the promotion rate, the manufacturers are not more likely to produce the LCPs and the retailers are more likely to promote the LCPs. Meanwhile, with the increase in the consumers' preference for the LCPs, the manufacturers are more likely to produce the LCPs and the retailers are more likely to promote LCPs.

(III) The influences of the consumers' sensitivity coefficients to the retail price on the probability

It is assumed that $k = 1$, $g = 1$, $c = 0.2$, $d = 0.2$, and $e = 1$ and that these parameters remain constant. The changes of the consumers' sensitivity coefficient, b, to retail price with the different values of the carbon tax rate, $h = 0.80, 0.65, 0.50, 0.35, 0.20$, are shown in Figure 5. It is shown that the probability, P, decreases with the consumers' sensitivity coefficients, b, as the retail price increases, and the growing speed also increases with the decrease of the carbon tax rate, h.

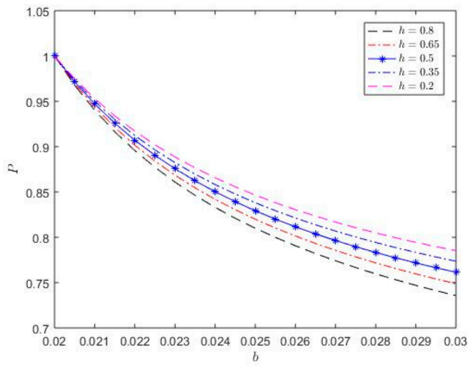


Figure 5. The influence of the consumers' sensitivity coefficients to the retail price on the probability.

From Figure 5, it is known that, with the increase in the consumers' sensitivity to the retail price, the manufacturers are not more likely to produce LCPs and the retailers are more likely to promote LCPs. Meanwhile, with the increase in the carbon tax, the manufacturers are not more likely to produce LCPs and the retailers are more likely to promote LCPs.

According to the results of the numerical simulation shown in Figures 3–5, some results are obtained as follows: (I) When consumers have a strong sensitivity to the emission reduction rate, the manufacturers will tend to produce LCPs and the retailers will not prefer to promote LCPs. On the other hand, when consumers have a strong sensitivity to the promotion rate, the retailers will prefer to promote LCPs and the manufacturers will not tend to produce LCPs. (II) When consumers have a strong preference for promoting LCPs, the retailers will prefer to promote the LCPs and the manufacturers will not be promoted to produce LCPs. Conversely, when the consumers have a strong preference for LCPs, the manufacturers will be promoted to produce LCPs and the retailers will not prefer to promote LCPs. (III) When consumers have a strong sensitivity to retail prices, the retailers are likely not to promote LCPs and the manufacturers are likely to produce LCPs. Meanwhile, when the carbon tax is high, the manufacturers will be likely to produce LCPs and the retailers will not prefer to promote LCPs.

5. Conclusions and Discussion

Given the current significance of low-carbon transformation as a strategic decision, this study specifically targets a two-stage LCSC consisting of a manufacturer and a retailer. The primary focus of this research is to investigate DM and coordination issues within the supply chain while incorporating consumers' preferences. Two models, namely a Stackelberg game model and a dynamic evolutionary game model, are developed to explore these issues and analyze the operational aspects of the supply chain. By taking into account the preferences of all involved parties, this study aims to minimize redundancy within the supply chain and promote efficient and sustainable practices that benefit both the environment and the stakeholders.

The main procedures of this study are outlined as follows: (1) Using Stackelberg game theory, Stackelberg equilibrium strategies for LCSC operations and DM are established. (2) The optimal profits of manufacturers and retailers under different equilibrium strategies are obtained by solving the profit models for the manufacturers and retailers. (3) The evolutionary game model is constructed based on the profits of the manufacturers and retailers under different strategy selection situations. (4) The evolutionary stability strategies at every equilibrium point are analyzed by solving the evolutionary game model. (5) By using the numerical simulation, the influences of the consumers' preferences on the evolutionary stability of the system are further analyzed.

Naturally, based on the results mentioned above, some of the findings are put forward as follows: (I) The low-carbon development of the industrial chain can be enhanced by raising consumers' awareness of environmental protection. When consumers become more conscious of the low-carbon and environmentally friendly aspects of products, manufacturers specializing in low-carbon products (LCPs) will experience increased profitability. Similarly, if consumers show greater interest in product promotion and popularity, retailers engaged in low-carbon promotion will generate higher profits. (II) The promotion of the industrial chain towards low-carbon development can be achieved by fostering consumers' preference for promotional activities carried out by retailers. The stronger consumers' preference is for retailers' promotion efforts, the more likely it is that manufacturers may not prioritize the production of LCPs. Conversely, retailers will be more inclined to promote LCPs. Additionally, as consumers' preference for LCPs strengthens, manufacturers are more likely to prioritize their production, leading to increased promotion of LCPs by retailers. (III) The low-carbon development of the industrial chain can be advanced by enhancing consumers' sensitivity to retail prices offered by retailers. The higher the level of sensitivity consumers exhibit towards retail prices, the more likely it is for manufacturers to produce LCPs, while retailers may opt not to extensively promote them. Changes in consumers' sensitivity coefficient to retail prices have a significant impact on both manufacturers and retailers. Notably, the impact on manufacturers is more pronounced compared to retailers.

There are some managerial implications, which are as follows: (I) Managers should possess a thorough understanding of consumer needs and preferences, integrating them into the decision-making and strategy development processes of the supply chain. By comprehending consumers' demand for low-carbon products, managers can optimize supply chain networks and enhance coordination among enterprises to effectively meet consumer expectations, thereby fostering customer satisfaction and bolstering market competitiveness. (II) Managers should holistically utilize models and optimization algorithms to evaluate diverse operational decisions and coordination strategies. By seeking the optimal balance point that simultaneously reduces carbon emissions and meets consumer needs, managers can effectively plan and optimize supply chain operations, thereby achieving sustainability and efficiency goals. (III) Managers should proactively engage in communication and interaction with consumers to grasp their requirements and expectations regarding low-carbon products and sustainable development. Establishing strong consumer relationships and feedback mechanisms enables managers to effectively adapt to evolving market dynamics, deliver offerings aligned with consumer preferences, and ultimately gain a competitive edge in the industry.

6. Limitations and Future Research

The research in this study provides rich theoretical references for scholars' work in related fields. However, the research in this study has some limitations. Firstly, in practical terms, there exist various approaches to reducing carbon emissions, which presents a constraint in this study. Manufacturers, for instance, can adopt new technologies, equipment, pollution control methods, and emission reduction strategies, while retailers can encourage consumers to purchase low-carbon products through leaflets, advertisements, and in-store promotions. The impact of consumers' low-carbon preferences is just one aspect among many potential approaches. Secondly, in real-world scenarios, the free-rider phenomenon may arise when one supplier unilaterally makes low-carbon decisions, which poses another limitation. This occurs because the decision made by one supplier will affect the profits of the other party, and the efforts of one party may increase the profits of the other party. Addressing the free-rider issue and promoting collaboration on low-carbon practices and marketing among suppliers should be considered crucial factors in addition to considering consumer preferences for low-carbon supply chain operations, decision-making, and coordination.

There is no doubt that some further work will be conducted in future research. Specifically, this study assumes a linear relationship between market demand, prices, and consumer preference coefficients. Since the competition and the imbalances of the supply and marketing in the market environment, and other factors, have an impact on the market's demand, it is necessary to consider the relationship between the market's demand and the influencing factors to be more in line with the practical market environment. Moreover, in practice, there are multiple suppliers in the operation and DM for the LCSC, in which the governments and consumers also act as the decision-makers in the game. Therefore, more in-depth research should be conducted for more suitable resolution of practical problems.

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