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Research Article

Behavior Choice and Emission Reduction in a Dynamic Supply Chain with a Capital-Constrained Retailer

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This paper studies the dynamic optimization of a low-carbon supply chain consisting of a manufacturer and a capital-constrained retailer. Considering market randomness and accumulation of production experience, a Stackelberg differential game model is constructed. In the game, the manufacturer is the leader and its pricing and emission reduction strategies over time are deduced in farsighted and myopic behaviors, respectively. In both behaviors, the emission reduction increases over time and a relatively low/high carbon price leads to skimming/penetrating pricing strategy of the manufacturer. Numerical study shows that the manufacturer must adopt a farsighted behavior for profit seeking except that consumers' low-carbon awareness is quite low, and the retailer also prefers the manufacturer to adopt this behavior. Increasing carbon price and consumers' low-carbon awareness benefits the manufacturer rather than the retailer. The governments can take measures to raise the carbon price to reduce the environmental impact.

1. Introduction

With the rapid development of world economies and the increasing frequency of human activities, the huge greenhouse gas emissions have brought severe challenges to the world climate. Developing a low-carbon economy is crucial to the sustainability of countries all over the world. On the one hand, the governments force enterprises to reduce emissions and advocate a low-carbon economy through various policies. For instance, a plan to reduce carbon intensity in 2030 by 43% from 2005 levels has been proposed by the European Union [1]. On the other hand, the enhancement of public low-carbon awareness drives consumers more inclined to buy low-carbon products [2]. According to an Accenture survey, more than 80% of consumers around the world consider the product's greenness when purchasing. This finding indicates that consumers' growing awareness of green has become a market driver, encouraging enterprises to make green improvements [3]. Therefore, firms need to formulate technological innovation, industrial restructuring, and other strategic plans, as well as operations management to achieve a sustainable development [4]. In reality, an increasing number of enterprises are committed to low-carbon production. For example, Motorola has achieved energy conservation and emission reduction by establishing the environmental management system in each stage of production [5]; fashion clothing manufacturers such as H&M and Levis have adopted new technologies to reduce carbon emissions [6].

In order to mitigate climate warming, worldwide governments have taken measures to curb greenhouse gas emissions [7]. Kyoto Protocol is an important agreement that points out the direction to solve this problem. The agreement puts forward the concept of carbon quota, and then several emission reduction policies such as carbon subsidy, carbon tax, mandatory carbon emissions regulation, and cap-and-trade system have been implemented. These policies are an important tool to promote firms to reduce carbon emissions [8, 9]. Consequently, firms must obey these policies and consider the issue of carbon emissions when they make decisions [10]. Given that the emission reduction is a long-term goal of governments, firms must continuously consider the effect of these policies and dynamically react [11]. Apart from external factors such as government policies, firms' behavior choice considerably affects their decision-makings in dynamic supply chains [12]. Generally, there are two choices in a dynamic decision-making: myopic and farsighted behaviors. A myopic firm only focuses on current interests, whereas a farsighted one considers overall interests, even at the expense of a certain time duration. Firms can present a preference to either of these behaviors and this preference depends on dynamic influence factors, channel structure, or other supply chain settings [13, 14].

However, retailers, usually as small and medium enterprises (SMEs), are plagued by capital constraints, which eventually impede the scale effects of the green supply chain [15]. Thus, SMEs must resort to financing from other institutes, among which, banks are the main lenders. Bank credit can help SMEs and even the corresponding partners in supply chains perform better when compared with no financing [16]. Due to the importance of SMEs to national economic development, many countries have encouraged banks to support SMEs by lowering the loan threshold. By 2018, the Industrial and Commercial Bank of China had set up 230 centers to provide financing services for more than 1 million small businesses, with loans exceeding 9 trillion yuan [17]. In particular, governments' support for energy conservation and emission reduction further increases the availability of bank loans for small and medium retailers in green supply chains. Moreover, the financing can also support SMEs' invest in emission reduction activities, thereby resulting in greener products [18]. In production process, the increase of production quantity and the improvement of proficiency will reduce manufacturing costs [19]. Such a "learning-by-doing" effect relieves the fund pressure of SMEs and thus cannot be ignored when SME managers make dynamic operational plans.

As abovementioned, SMEs must simultaneously make decisions on operations management, emission reduction, and financing when they are subject to capital constraints and cap-and-trade regulations. Considering these factors comprehensively, we put forward the following research questions.

How does the manufacturer make farsighted or myopic decisions under cap-and-trade system?

How does the capital-constrained retailer determine its optimal order quantity in the cooperation of a farsighted manufacturer? What about the retailer's decision when cooperating with a myopic manufacturer?

How does the manufacturer choose farsighted or myopic behavior?

We establish a Stackelberg differential game model to answer the above questions. This model is solved via the Hamilton function. The analytical and numerical methods are used to compare the decision-makings and performances between the manufacturer's different strategy choices and analyze the influences of several key parameters in terms of economic and environmental impacts.

The remainder of the paper is organized as follows. Section 2 reviews the related literature. Section 3 formulates the model. Section 4 discusses the optimal decision-makings of farsighted and myopic manufacturers, respectively. Section 5 draws numerical analysis and discusses the effects of several key parameters. Section 6 concludes this study.

2. Literature Review

Three streams of literature are closely related to this study, that is, low-carbon supply chains, learning-by-doing, and supply chain finance. In the following, each stream is reviewed and compared with this study.

2.1. Low-Carbon Supply Chains. Since governments formulated relevant policies on carbon emissions, low-carbon issue has been attracting an increasing number of supply chain scholars. For instance, Yang and Xu [20] explored the dynamic investment and production decisions in a closed-loop supply chain. Analysis of the optimal conditions for multiple participants that compete in a noncooperative manner concluded that subsidies can stimulate investments of factories in emission reduction technology under governments' emission permits. Saxena, Jain, and Sharma [21] combined business economics with carbon tax policy and proposed a comprehensive strategic planning model for tire remanufacturing supply chain. Yuyin and Jinxi [22] proposed a carbon cost-sharing contract and demonstrated that the policies of carbon tax and government subsidy can promote energy conservation and emission reduction in industrial practice. Under mandatory carbon emissions regulation, Xu, Qi, and Bai [23] showed that the amount of emission permits allocated to members of dual-channel supply chains and whether these permits are fully utilized affect the interests of suppliers and consumers. In a regulation of subsidies (penalties) for manufacturing low-carbon (high carbon) products, Heydari et al. [24] investigated a retailer's low-carbon sales efforts that can promote customers to buy low-carbon products instead of high carbon products; the authors developed a novel cost-revenue sharing combined with a buyback scheme to improve the supply chain performance. Considering cap-and-trade system, Hong, Chu, and Yu [25] studied manufacturing plans, including the retailer's pricing and ordering strategies, and discussed the impact of this system on retailer's strategies and expected profits. Wang et al. [26] demonstrated that the implementation of emissions trading mechanism encourages suppliers to choose low-carbon partners. The authors conducted empirical research on the pilot emissions trading mechanism in Hubei, China, to explore the effect of carbon quota constraints. Wang, Cheng, and Zhang [27] pointed out that the emission trading mechanism is more flexibility and cost-effectiveness and can become a common way to achieve emission reduction targets. Peng, Pang, and Cong [28] and Xu, Wang, and Zhao [29] improved revenue sharing contracts that can coordinate supply chains via emission reduction subsidy and cost-sharing mechanisms, respectively. The results showed that governments' carbon quota and trading rules can effectively reduce emissions and hence achieve coordinated development between economy and environment. Following these studies, this research investigated the effect of cap-and-trade regulation on supply chain decision-makings.

Given that considerable firms pursue a long-term development goal, researchers have increasingly focused on the decision-making behavior in supply chains and explored the dynamics of influencing factors [30, 31]. For instance, Gutierrez and He [13] analyzed the dynamic strategic interaction between manufacturers and retailers in decentralized distribution channels. They demonstrated that, in some cases, manufacturers perform better when cooperating with farsighted retailers, and in other cases, manufacturers prefer to cooperate with myopic retailers. Zhang et al. [32] concluded that a dynamic pricing strategy benefits manufacturers more than a static one. In addition, the farsighted behavior adopted by both channel members leads to the lowest supply chain efficiency, whereas that behavior only adopted by the retailer achieves the highest efficiency. Liu et al. [14] argued that the behavior choice in supply chains mostly falls into a prisoner's dilemma; i.e., farsighted way is a better choice for any member, but myopia benefits the entire supply chain. Therefore, the behavior choice must be discussed to offer the best decision-making suggestions for a specific problem in dynamic supply chains.

Different from the above literature, this study simultaneously considers the cap-and-trade regulation and behavior choice in dynamic decision-makings. A similar study is [12], wherein the capital constraints are not included.

2.2. Learning-by-Doing. As aforementioned, learning-by-doing effect features a great effect on reduction of manufacturing cost as time passes by. Thus, several studies have investigated this factor on firms' decision-makings and profits. For instance, Wei, Yi, and Fu [33] pointed out that experience accumulation from practical learning can improve the efficiency of investment on production capacity and pollution abatement. Li and Ni [34] also showed that learning-by-doing affects the process and product innovation, as well as their complementarity relationship. Talukdar [35] found that a marginal decline in markup can benefit future productivity when the learning rate of firms increases. Kogan and El Ouardighi [36] investigated a competition for partially substitutable products and indicated that prices increase over time if learning-by-doing is more effective than quality improvement. Through the growth model, Bouché [37] showed that learning-by-doing can realize the endogenous growth of firms. Note that the above studies only investigate the decision-makings of a sole firm or a competitive duopoly market. In the perspective of supply chains, Zhang, Tang, and Zhang [38] investigated a retailer-leaded supply chain in which two members share the green investment cost; the authors revealed that the manufacturer should govern the investment level unless the retailer is endowed with a large bargaining power. Further considering reference emission effect, Yu et al. [19] compared cost-sharing and revenue sharing strategies and indicated that the manufacturer prefers the revenue sharing and the supply chain performance will be improved when the manufacturer's learning ability increases. In a two-period model, Deng, Guan, and Xu [39] examined the competition regarding learning-by-doing in a one-manufacturer-two-OEMs supply chain and demonstrated that this effect intensifies the price competition and outsourcing to the manufacturer brings OEMs a high learning benefit. Using a case study method, Kalantary and Farzipoor Saen [40] developed a dynamic DEA model and stated that learning-by-doing significantly affects a supply chain's sustainability.

Following these studies, we consider the learning-by-doing effect. This effect can also be found to investigate decision-makings of low-carbon supply chains in [19, 38]. Our study differs with these literatures on that we examine the dynamic decision-making behaviors.

2.3. Supply Chain Finance. Due to the cash-poor of SMEs, the crossover research of operations management and financial decision-making has recently attracted considerable attention in supply chains. For instance, Wang, Yu, and Jin [41] pointed out that capital constraints are an important factor that restricts the development of SME e-commerce platforms. Wang, Cheng, and Zhang [27] showed that bank credit can enhance the overall efficiency of the supply chain with a SME retailer and achieve Pareto improvement for both supply chain members via a functional revenue sharing contract. Considering two retailers with limited capital, Yang, Miao, and Zhao [42] examined the impact of credit strategy on green supply chain performance. Jin, Zhang, and Luo [43] studied three modes of bank financing: separately, with trade credit, and with supplier's guarantee. By comparing the equilibrium strategies under these modes, the resulting conclusion provides guidance for supply chain members. Wang, Chen, and Liu [18] investigated a remanufacturing planning problem with a capital-constrained manufacturer. The result showed that the manufacturer is more willing to remanufacture high-quality second-hand products at a low-carbon emission level when banks or capital markets supply sufficient capital financing. Cong, Pang, and Peng [44] considered a random yield supply chain and explored effects of green finance on emission reduction. The authors demonstrated that the green finance can make cap-and-trade system present a positive effect on emission reduction when manufacturers feature a low or medium emission level, whereas yield uncertainty decreases this positive effect. In a manufacturing supply chain with a capital-constrained manufacturer, Heydari and Mirzajani [45] proposed a revenue sharing scheme, which not only achieves a win-win situation for both manufacturer and supplier, but also benefits the environment.

This study differs with the above literature on that we examine the financing problems in a dynamic setting of supply chains. In a multiperiod setting, Lekkakos and Serrano [46] investigated the effects of traditional factoring and reverse factoring strategies on a supplier's inventory replenishment decision; Tang and Zhuang [47] proposed a blockchain-driven financing and revealed that this financing scheme can improve efficiency in both financing and production. In difference, our study uses the differential game framework to investigate dynamic decision-makings in capital-constrained supply chains.

2.4. Literature Comparison and This Paper's Contributions. Table 1 provides a comparison between this study and the most related works. Although Lekkakos and Serrano [46] and Tang and Zhuang [47] addressed supply chain financing in a dynamic setting, these works did not consider learning-by-doing effect and low-carbon decisions. Most of other works listed in Table 1 addressed low-carbon decisions and learning-by-doing effect; however, they did not consider the financing in supply chains. This paper simultaneously addresses learning-by-doing, supply chain financing, and low-carbon decisions. The contributions of this study are threefold.

To the best of knowledge, the existing literature lacks the research on capital-constrained supply chains in a differential game framework. This study fills this gap.

Another contribution of this study is that we investigate the impact of production experience accumulation on decision-makings of emission reduction, pricing, and order quantity.

The research findings and corresponding management implications can guide firm managers to make operational decisions in supply chains and governments to take measures to reduce the carbon emissions of firms.

3. Model

This paper studies the long-term decision-making process of a supply chain consisting of a manufacturer and a capital-constrained retailer. The manufacturer acts as the leader to determine the emission reduction and wholesale price at each time period. The following retailer determines the order quantity according to the market demand and wholesale price. Moreover, the retailer needs to borrow money in banking market to conduct purchase activities. Figure 1 demonstrates the corresponding relations among corresponding stakeholders in the supply chain. The learning-by-doing affects the unit cost in each period. Given that emissions are emitted when manufacturing, the manufacturer must trade the insufficient/remainder carbon quota in the carbon market.

3.1. Notations

$\Delta e(t)$: amount of emission reduction per unit product at time t

$D(t)$: market demand at time t

α: potential market size, a random variable

θ: carbon sensitivity coefficient

β: cost coefficient of emission reduction

$Q(t)$: cumulative sales from time 0 to t

c_0: initial cost per unit product

c_1: learning speed

$c(Q(t))$: cost per unit product at time t

$C(\Delta e(t))$: emission reduction cost at time t

P_c: price per unit emission permit

e_0: amount of initial emissions per unit product

E_0: carbon quota of the manufacturer for each time period

$r(t)$: banks' lending rate at time t

$\Pi(t)$: expected profit

ρ: risk-free discount rate, $\rho > 0$

M, R: subscripts used to represent manufacturer and retailer, respectively

F, O: superscripts used to represent farsighted and myopic behaviors, respectively

$*$: superscript used to represent the optimal solutions

3.2. Basic Assumptions. Given that customers prefer to purchase low-carbon products, the emission reduction of the manufacturer affects the market demand [48, 49], which can be expressed as

$$D(t) = \alpha + \theta\Delta e(t), \tag{1}$$

where $\theta \geq 0$ represents the customers' response to carbon emissions. A larger θ indicates that customers feature more willingness to purchase low-carbon products. This demand function is composed of two items. The first item reflects the basic demand and is depicted by a random variable. The second item captures the effect of emission reduction on the demand. This function form has been adopted by Gong et al. [50], wherein the second item describes the effect of price instead.

The manufacturer can reduce carbon emissions by investing in green technologies, improving production processes, etc. The emission reduction cost can be regarded as a function of emission reduction per unit product. Following Zhang, Wang, and Shanain [51], Yi and Li [22], and Yu et al. [19], a quadratic function is used and thus the investment cost of emission reduction at time t is given by

$$C(\Delta e(t)) = \frac{1}{2}\beta(\Delta e(t))^2. \tag{2}$$

The manufacturer follows the principle of learning-by-doing in the production process, thereby meaning that the unit production cost of the manufacturer decreases with the accumulation of production experience. Following Zhang, Tang, and Zhang [52], this study uses linear learning effect to characterize the impact of learning-by-doing. Thus, the unit production cost at time t is given by

$$c(Q(t)) = c_0 - c_1 Q(t). \tag{3}$$

Although the unit product cost decreases with the increase of cumulative production, it cannot be negative, i.e., $c(Q(t)) > 0$.

TABLE 1: Literature comparison regarding low-carbon decision or financing in dynamic supply chains.

Paper	Dynamic effect	Supply chain financing	Low-carbon policy	
			Tax	Cap-and-trade
Lekkakos and Serrano [46]	Inventory replenishment	x		
Tang and Zhuang [47]	Cash balance	x		
Kalantary and Farzipoor Saen [40]	Learning-by-doing			
Zhang, Tang, and Zhang [38]	Learning-by-doing			
Wang et al. [12]	Reference emission effect			x
Yu et al. [19]	Learning-by-doing and reference emission		x	
This paper	Learning-by-doing	x		x

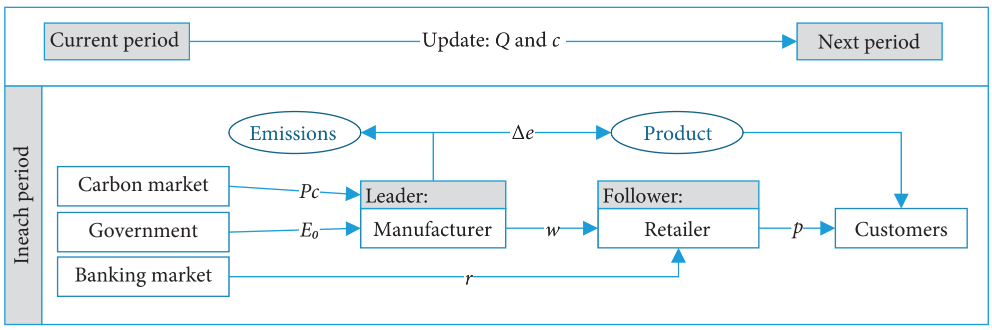

FIGURE 1: Supply chain structure.

The manufacturer can be allocated a fixed quota of emission permits in each time period. If the actual carbon emissions exceed the quota, the manufacturer must buy the permits in carbon trading markets; if the manufacturer has a surplus quota, it can sell the permits. Then the manufacturer's carbon emission cost at time t can be written as [27]

$$P_c\Big(\big(e_0 - \Delta e(t)\big)\dot{Q}(t) - E_0\Big). \tag{4}$$

Note that $\dot{Q}(t)$ is the sales volume of manufacturer in each period given that $Q(t)$ is the cumulative sales. Given that the carbon price is determined by the external trading market, this study assumes this price is independent with time; otherwise, we cannot obtain the equilibrium solutions by analytical methods.

Without loss of generality, the retail price is normalized to 1. This assumption is commonly used in literature such as Wang, Cheng, and Zhang [27], Jing, Chen, and Cai [53], and Chen [54]. Inventory and out-of-stock costs in the supply chain are neglected. The retailer's capital is zero in each period and it can finance from banks. The manufacturer and retailer are rational decision-makers. The retailer has limited liability for bank debts and the banking market is a completely competitive market. These hypotheses can be found in literature such as Jing, Chen, and Cai [53], Chen [54], and Deng et al. [55]. We assume that the manufacturer makes decisions in farsighted or myopic behavior, while the retailer only considers myopic decisions.

3.3. Decision-Making Process. This study considers a Stackelberg differential game between manufacturer and retailer in a finite time horizon $[0, T]$. The leading manufacturer determines current wholesale price $w(t)$ and emission reduction $\Delta e(t)$. The following retailer reacts and makes a decision on its order quantity $\dot{Q}(t)$. Banks finally announce lending rate $r(t)$.

We solve the equilibrium solutions in banking market and distribution channel by backward induction. We first consider the banking market. At the beginning of each period, the retailer borrows money from banks and then pays for the goods. Under the assumption of limited liability of retailer, at the end of each period, if sales revenue of the retailer in this period is less than the total of principal and interest, only the income will be used to repay the loan; otherwise, both the principal and interest will be repaid. Following Jing, Chen, and Cai [53], in a perfectly competitive banking market, the equilibrium condition is zero return for banks, i.e.,

$$\begin{aligned} &E\min\Big\{\min\big\{D(t),\dot{Q}(t)\big\}, w(t)\dot{Q}(t)\big(1+r^*(t)\big)\Big\} \\ &\quad = w(t)\dot{Q}(t). \end{aligned} \tag{5}$$

The retailer only considers current profit, and hence its expected profit is given by

$$\Pi_R(t) = E\Big(\min\big\{D(t),\dot{Q}(t)\big\} - w(t)\dot{Q}(t)\big(1+r^*(t)\big)\Big)^+, \tag{6}$$

where $x^+ = x$ if $x \geq 0$, and $x^+ = 0$ otherwise.

Lemma 1 (see Jing et al. [53]). *If* $(1 + r^*(t))w(t) < 1$, *then the decision-making problem of the retailer coincides with the standard newsvendor problem, i.e.,*

$$\max \Pi_R'(t) = \max\Big\{E\min\big\{D(t),\dot{Q}(t)\big\} - w(t)\dot{Q}(t)\Big\}. \tag{7}$$

Note that the retailer is follower in the supply chain and only considers the current profit. We can first solve the retailer's ordering strategy and then solve the manufacturer's pricing and emission reduction strategies in farsighted and myopic cases, respectively. To obtain an analytical solution, we assume that the potential market size α satisfies a uniform distribution on interval $[a, b]$. According to the first-order condition, we have the following equation that maximizes the retailer's profit:

$$\frac{d\Pi_R^{\prime}(t)}{\mathrm{d}\dot{Q}(t)} = \frac{b + \theta\Delta e(t) - \dot{Q}(t)}{b - a} - w(t) = 0. \tag{8}$$

Then we obtain

$$\dot{Q}(t) = b - (b - a) w(t) + \theta\Delta e(t). \tag{9}$$

The following inequality must be satisfied to ensure that the order quantity of each period is positive.

$$b - (b - a)(c_0 + P_c e_0) \geq 0. \tag{10}$$

4. Farsighted and Myopic Solutions

The manufacturer's decision-making behavior has a significant influence on the supply chain members' profits and the resulting environmental impact. Consequently, this section provides the equilibrium solutions in these two behaviors, respectively. Then, the influence is investigated in the following section.

4.1. Farsighted Manufacturer Case. Farsighted manufacturer means the manufacturer focuses on long-term interests and pursues the maximization of overall profits in the whole duration $[0, T]$. In this case, the manufacturer's decision-makings must be based on the maximization of the retailer's profit in any period. Thus, the manufacturer's optimal control problem is given by (for the convenience of writing and reading, time stamp t is not listed below)

$$\max_{\Delta e^F(\cdot), w^F(\cdot)} \Pi_M^F = \max_{\Delta e^F(\cdot), w^F(\cdot)} \int_o^T e^{-\rho t}\left(w^F\dot{Q}^F - \left(c_0 - c_1 Q^F\right)\dot{Q}^F - \frac{1}{2}\beta\left(\Delta e^F\right)^2 - P_c\left(\dot{Q}^F\left(e_0 - \Delta e^F\right) - E_0\right)\right)\mathrm{d}t, \tag{11a}$$

$$\text{s.t.}\ \dot{Q}^F = b - (b - a)w^F + \theta\Delta e^F. \tag{11b}$$

Proposition 1. *In farsighted case, the optimal emission reduction and wholesale price are*

$$\Delta e^{*F} = \frac{1}{X_1}\left(c_1 X_2 Q^{*F} + X_2\lambda + X_3\right), \tag{12}$$

$$w^{*F} = \frac{1}{X_1}\left(c_1 X_4 Q^{*F} + X_4\lambda + X_5\right), \tag{13}$$

where

$$\begin{pmatrix} Q^{*F} \\ \lambda \end{pmatrix} = \begin{pmatrix} \dfrac{2Y_1}{\rho - 2c_1Y_1 + \sqrt{\rho^2 - 4\rho c_1 Y_1}}k_1 e^{r_1 t} + \dfrac{2Y_1}{\rho - 2c_1Y_1 - \sqrt{\rho^2 - 4\rho c_1 Y_1}}k_2 e^{r_2 t} - \dfrac{Y_2}{c_1 Y_1} \\ k_1 e^{r_1 t} + k_2 e^{r_2 t} \end{pmatrix}, \tag{14}$$

and $X_1 - X_5$, Y_i, r_i, $k_i\ (i = 1, 2)$ *are given in the following proof.*

Proof. According to the manufacturer's optimal control problem in equations (11a) and (11b), we can establish the Hamilton function as follows:

$$\begin{aligned} H = {} & w^F\left(b - (b - a)w^F + \theta\Delta e^F\right) - \left(c_0 - c_1 Q^F\right)\left(b - (b - a)w^F + \theta\Delta e^F\right) \\ & - \frac{1}{2}\beta\left(\Delta e^F\right)^2 - P_c\left(\left(b - (b - a)w^F + \theta\Delta e^F\right)\left(e_0 - \Delta e^F\right) - E_0\right) + \lambda\left(b - (b - a)w^F + \theta\Delta e^F\right). \end{aligned} \tag{15}$$

According to the first-order condition, we have

$$\frac{\partial H}{\partial w^F} = b - 2(b-a)w^F + \theta\Delta e^F + \left(c_0 - c_1 Q^F\right)(b-a) + P_c(b-a)\left(e_0 - \Delta e^F\right) - \lambda(b-a) = 0, \tag{16}$$

$$\frac{\partial H}{\partial \Delta e^F} = \theta w^F - \theta\left(c_0 - c_1 Q^F\right) - \beta\Delta e^F - P_c\left(\theta e_0 + (b-a)w^F - b - 2\theta\Delta e^F\right) + \lambda\theta = 0. \tag{17}$$

Combining equation (17) with equation (18), we obtain the manufacturer's emission reduction and wholesale price as follows:

$$\Delta e^F = \frac{1}{X_1}\left(c_1 X_2 Q^F + X_2\lambda + X_3\right), \tag{18}$$

$$w^F = \frac{1}{X_1}\left(c_1 X_4 Q^F + X_4\lambda + X_5\right), \tag{19}$$

where $X_1 = 2\beta(b-a) - (\theta + P_c(b-a))^2$, $X_2 = (b-a)(P_c + \theta)$, $X_3 = b\theta - P_c c_0 (b-a)^2 - c_0\theta(b-a) - P_c(e_0\theta - b)(b-a)$, $X_4 = \theta^2 - (\beta - P_c\theta)(b-a)$, and $X_5 = P_c(e_0\theta - b)(P_c(b-a) - \theta) + b(\beta - P_c\theta)(b-a) + P_c e_0(\beta - 2P_c\theta)(b-a) - \theta^2 c_0$. X_1 must be positive to ensure the existence of extremum points, i.e., $X_1 > 0$.

From equation (16), we have

$$\dot{\lambda} = \rho\lambda - \frac{\partial H}{\partial Q^F} = \rho\lambda - c_1\left(b - (b-a)w^F + \theta\Delta e^F\right). \tag{20}$$

Substitute equations (18) and (19) into (20), solve the resulting differential equation, and hence we can obtain

$$\begin{pmatrix} Q^{*F} \\ \lambda \end{pmatrix} = \begin{pmatrix} \dfrac{2Y_1}{\rho - 2c_1Y_1 + \sqrt{\rho^2 - 4\rho c_1 Y_1}} k_1 e^{r_1 t} + \dfrac{2Y_1}{\rho - 2c_1Y_1 - \sqrt{\rho^2 - 4\rho c_1 Y_1}} k_2 e^{r_2 t} - \dfrac{Y_2}{c_1 Y_1} \\ k_1 e^{r_1 t} + k_2 e^{r_2 t} \end{pmatrix}, \tag{21}$$

where $Y_1 = X_2/X_1\theta - X_4/X_1(b-a)$, $Y_2 = b + X_3/X_1\theta - X_5/X_1(b-a)$, $r_1 = \rho + \sqrt{\rho^2 - 4\rho c_1 Y_1}/2$, $r_2 = \rho - \sqrt{\rho^2 - 4\rho c_1 Y_1}/2$.

Combining equation (21) with boundary conditions $\lambda(T) = 0$ and $Q^F(0) = 0$, k_1 and k_2 can be obtained as follows:

$$\begin{aligned} k_1 &= \frac{2c_1Y_2}{\left(\rho - 2c_1Y_1 - \sqrt{\rho^2 - 4\rho c_1Y_1}\right) - \left(\rho - 2c_1Y_1 + \sqrt{\rho^2 - 4\rho c_1Y_1}\right)e^{(r_1 - r_2)T}}, \\ k_2 &= \frac{2c_1Y_2}{\left(\rho - 2c_1Y_1 + \sqrt{\rho^2 - 4\rho c_1Y_1}\right) - \left(\rho - 2c_1Y_1 - \sqrt{\rho^2 - 4\rho c_1Y_1}\right)e^{(r_2 - r_1)T}}. \end{aligned} \tag{22}$$

Substitute equation (21) into (18) and (19) and thus we obtain the expressions of w^F and Δe^F as shown in equations (12) and (13).

According to the conclusion of Proposition 1, the following corollary can be drawn. □

Corollary 1. *Denoting* $\overline{P_c} \equiv b - c_0(b-a)/(b-a)e_0$, $\widetilde{P}_c \equiv \beta(b-a) - \theta^2/\theta(b-a)$. *In farsighted case:*

(1) The optimal emission reduction Δe^{*F} *increases over time.*

(2) If $\overline{P_c} < \widetilde{P}_c$, *i.e.,* $e_0 > (b - c_0(b-a))\theta/(b-a)\beta - \theta^2$, *the optimal wholesale price* w^{*F} *decreases over time.*

(3) If $\overline{P_c} \ge \widetilde{P}_c$, *i.e.,* $0 < e_0 \le (b - c_0(b-a))\theta/(b-a)\beta - \theta^2$:

when $P_c \in (0, \widetilde{P}_c)$, *the optimal wholesale price* w^{*F} *decreases over time;*

when $P_c \in (\widetilde{P}_c, \overline{P_c}]$, *the optimal wholesale price* w^{*F} *increases over time;*

when $P_c = \widetilde{P}_c$, *the optimal wholesale price* w^{*F} *remains unchanged over time.*

Proof. Given that equations (18) and (19) are derived from time t, we have $\dot{w}^F = X_4/X_1(c_1\dot{Q} + \dot{\lambda})$ and $\Delta\dot{e}^F = X_2/X_1(c_1\dot{Q} + \dot{\lambda})$. Combining $\dot{\lambda} = \rho\lambda - c_1\dot{Q}$, we obtain $\dot{w}^F = X_4/X_1\rho\lambda = \rho\lambda/X_1(\theta^2 - (\beta - P_c\theta)(b-a))$ and $\Delta\dot{e}^F = X_2/X_1\rho\lambda = \rho\lambda/X_1(b-a)(P_c + \theta)$.

Noting that $\dot{\lambda} < 0$ and $\lambda(T) = 0$, we can deduce $\lambda(t) > 0$, $t \in [0, T)$ and hence $\Delta\dot{e}^F > 0$. This means that the optimal emission reduction Δe^F always increases with time t. Thus, we obtain the first conclusion in this corollary.

Letting $\dot{w}^F = 0$, we have $P_c = \widetilde{P}_c \equiv \beta(b-a) - \theta^2/\theta(b-a)$. When $P_c < \widetilde{P}_c$, $\dot{w}^F < 0$; when $P_c > \widetilde{P}_c$, $\dot{w}^F > 0$. According to equation (10) and $P_c \leq \overline{P_c} \equiv b - c_0(b-a)/(b-a)e_0$, we obtain the second and third conclusions in this corollary.

The increase of emission reduction will stimulate market demand and lead to the increase of the retailer's optimal order quantity. This effect plus learning-by-doing results in the manufacturer's increasing sales revenue over time. Another part of the manufacturer's income or expenditure comes from carbon emissions. On the one hand, increasing emission reduction is accompanied with increasing cost. On the other hand, emission reduction reduces the consumption of emission permits. Corollary 1 shows that when the manufacturer adopts farsighted strategy, the optimal amount of emission reduction increases over time. This conclusion means that the benefit of emission reduction brought by the increase of order volume and emission permit saving as well as learning-by-doing effect are enough to make up for the investment cost of emission reduction. Therefore, increasing the level of emission reduction over time benefits the manufacturer.

Corollary 1 further demonstrates that the farsighted manufacturer will adopt penetrating pricing strategy if the carbon price is relatively high. One reason is that the increasing sales volume produces increasing emissions over time. The sales revenue cannot compensate for the costs of investing emission reduction and purchasing emission permits. Thus, the manufacturer must increase the wholesale price over time. If the carbon price is relatively low, the increasing sales revenue over time can make up for the expenditures of higher emission reduction level and more emission permit purchase. As a result, the manufacturer will reduce wholesale price over time. □

4.2. Myopic Manufacturer Case. The manufacturer pursues the optimal profit in each period rather than the entire duration when it makes a myopic decision. In this case, the manufacturer's optimal control problem is given by

$$\max_{\Delta e^O(\cdot), w^O(\cdot)} \Pi_M^O = \max_{\Delta e^O(\cdot), w^O(\cdot)} \left(w^O \dot{Q}^O - \left(c_0 - c_1 Q^O\right)\dot{Q}^O - \frac{1}{2}\beta\left(\Delta e^O\right)^2 - P_c\left(\dot{Q}^O\left(e_0 - \Delta e^O\right) - E_0\right)\right), \tag{23a}$$

$$\text{s.t. } \dot{Q}^O = b - (b-a)w^O + \theta\Delta e^O. \tag{23b}$$

Proposition 2. *In myopic case, the cumulative sales curve, emission reduction, and wholesale price are*

$$Q^{*O} = \frac{B}{A}\left(e^{At} - 1\right), \tag{24}$$

$$\Delta e^{*O} = \frac{b\theta - P_c\left(c_0 - c_1 Q^{*O}\right)(b-a)^2 - P_c^2 e_0(b-a) + P_c b(b-a) - P_c e_0 \theta(b-a) - \theta\left(c_0 - c_1 Q^{*O}\right)(b-a)}{2\beta(b-a) - (\theta + P_c(b-a))^2}, \tag{25}$$

$$w^{*O} = \frac{\left((\beta - P_c\theta)(b-a) - \theta^2\right)\left(c_0 - c_1 Q^{*O}\right) - P_c(b-a)\left(P_c(b+\theta e_0) - \theta\right) + \beta\left(P_c\theta(b-a) + b\right)}{2\beta(b-a) - (\theta + P_c(b-a))^2}, \tag{26}$$

where A, B are given in the proof.

Proof. According to the first-order condition that maximizes the manufacturer's objective function, we have

$$\frac{\partial \Pi_M^O}{\partial w^O} = b + \theta\Delta e^O - 2(b-a)w^O + \left(c_0 - c_1 Q^O\right)(b-a) + P_c\left(e_0 - \Delta e^O\right)(b-a) = 0, \tag{27}$$

$$\frac{\partial \Pi_M^O}{\partial \Delta\, e^O} = \theta w^O - \theta\left(c_0 - c_1 Q^O\right) - \beta\Delta e^O + P_c\left(b + 2\theta\Delta e^O - \theta e_0 - (b-a)w^O\right) = 0. \tag{28}$$

Combining equation (27) with equation (28), we can obtain equations (25) and (26). Substituting equations (25) and (26) into (23b) and noting that $Q(0) = 0$, the cumulative sales curve can be obtained as shown in equation (20), where $A = \beta c_1 (b-a)^2/2\beta(b-a) - (\theta + P_c(b-a))^2$, and $B = (\beta\ (b - P_c e_0) - \theta(bP_c + c_1\theta) - P_c e_0 \theta(P_c + \theta))\ \ (b-a) + (\beta(c_1 - c_0) + P_c\theta(P_c e_0 - c_1 - 1))(b-a)^2/2\beta(b-a) - (\theta + P_c(b-a))^2$.

According to Proposition 2, the following corollary can be drawn. □

Corollary 2. *In myopic case, the change of the optimal wholesale price and emission reduction over time is the same as that in farsighted case.*

The proof process of Corollary 2 is similar to that of Corollary 1 and hence omitted here.

Corollary 2 shows that whether the manufacturer adopts farsighted or myopic behavior, its optimal pricing and emission reduction strategies feature the same trend. However, supply chain performance differs in these behaviors and the comparison between these behaviors will be detailedly illustrated in the following section.

5. Numerical Analysis

The equilibrium solutions are so complex that we resort to numerical method to compare the performances between manufacturer's different strategy choices and analyze the influences of several key parameters. Following [27, 51, 52], relevant parameter values are set as $a = 10$, $b = 30$, $\rho = 0.01$, $c_0 = 0.15$, $c_1 = 0.0001$, $\beta = 10$, $e_0 = 1$, $E_0 = 10$, $T = 20$, $\theta = 3$, and $P_c = 0.1$. This study adopts two criteria, namely, economic and environmental impacts. The economic impact refers to the manufacturer's and retailer's profit. The environmental impact can be measured by the total emissions [56], as shown in the following equation:

$$\text{Environmental impact} = (e_0 - \Delta e)\dot{Q}. \tag{29}$$

Firstly, we exhibit the manufacturer's and retailer's profits with different initial values of unit production cost in farsighted and myopic behavior choices, as shown in Figures 1 and 2, where "MF"/"RF" and "MO"/"RO" represent the manufacturer/retailer's profits in farsighted and myopic behaviors, respectively. Figure 2 shows that the manufacturer gains more profit when adopting a farsighted behavior than adopting a myopic one for each initial value of unit production cost. In other words, a farsighted manufacturer can formulate better strategies than a myopic one, because the farsighted behavior considers future changes and adopts timely response strategies. In both behaviors, the profit decreases with the increase of c_0. Figure 3 shows that the retailer's profit almost features the same trend as the manufacturer, i.e., higher when cooperating with a farsighted manufacturer than that with a myopic one and lower when suffering a higher c_0. Moreover, we find that the behavior choice has a greater impact on the retailer than that on the manufacturer. And the myopic manufacturer makes the retailer earn no money

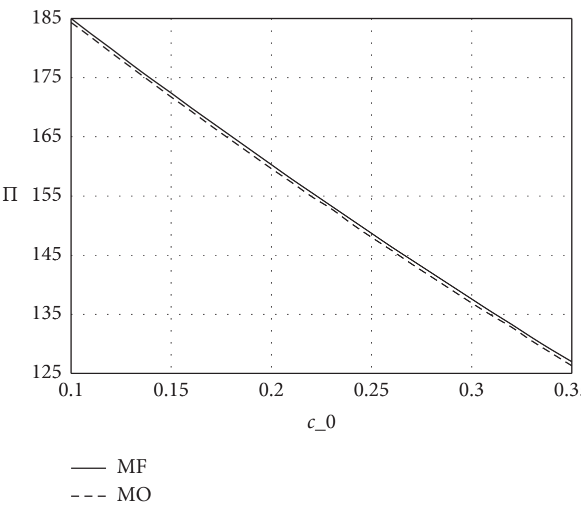

Figure 2: Impact of initial value of unit production cost on manufacturer's profit.

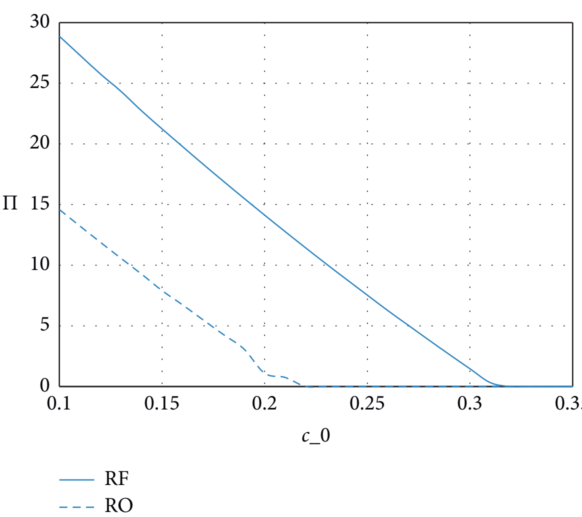

Figure 3: Impact of initial value of unit production cost on retailer's profit.

when involving $c_0 \geq 0.22$, whereas the farsighted manufacturer does that involving a higher threshold (i.e., $c_0 \geq 0.32$). One reason is that the manufacturer is leader in the game and it can transfer this negative impact to the retailer. Consequently, the retailer transfers this impact to banks and hence it will not lose money.

The impact of initial value of unit production cost on environment is shown in Figure 4, wherein we set values of this parameter as 0.1, 0.15, and 0.2. The curves in this figure demonstrate that a low value of c_0 harms the environment in both farsighted and myopic behaviors. The reason is that as the manufacturing cost decreases, the manufacturer will reduce the wholesale price and thus the retailer will increase the order quantity. Although such a cost decrease involves a reductive emissions of unit product, this reduction cannot offset the impact by order increment. Moreover, in each value setting of c_0, the farsighted behavior shows a higher environmental impact in the initial period of the planning

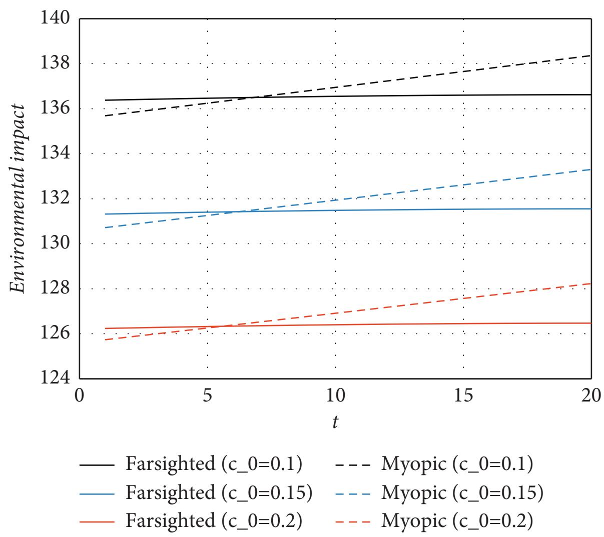

Figure 4: Impact of initial value of unit production cost on environment.

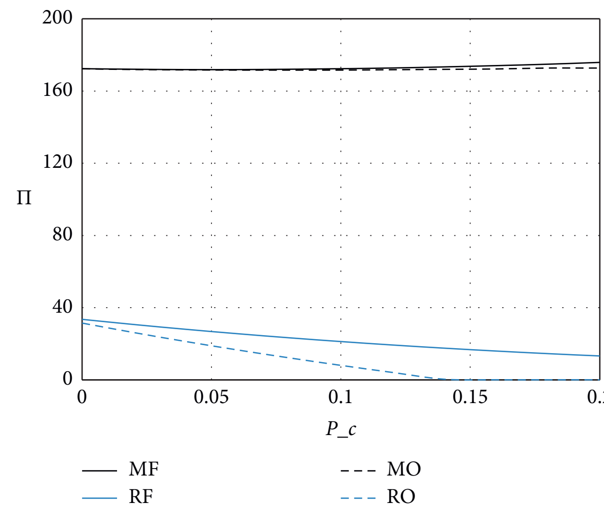

Figure 5: Impact of carbon price on profits in farsighted and myopic cases.

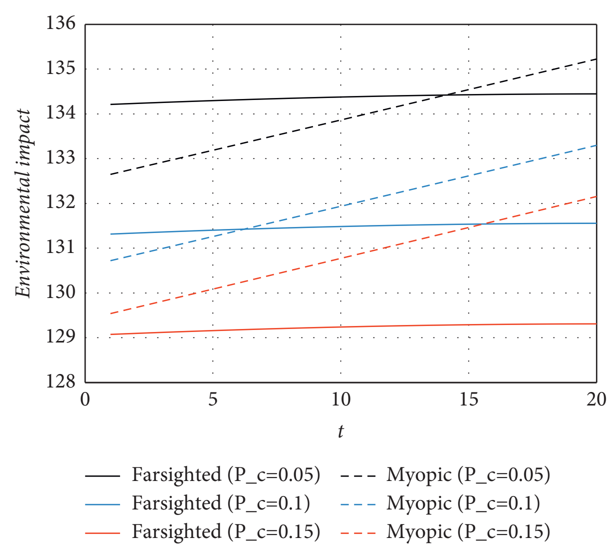

Figure 6: Impact of carbon price on environment.

horizon and lower impact in the late period of the horizon than the myopic one. Overall, the farsighted behavior is beneficial to the environment.

Next, we vary the carbon price and keep other parameters unchanged to study the impact of carbon price on profits. Figure 5 plots the result. When the carbon price increases, the manufacturer's and retailer's profits feature an opposite trend in both farsighted and myopic behaviors; i.e., the manufacturer's increases and the retailer's decreases. This is because a higher carbon price stimulates the manufacturer to exert more effort on emission reduction and hence causes a higher saving of emission cost. Meanwhile, the leading manufacturer can raise the wholesale price to transfer the negative impact of high emission cost to the retailer. As a result, the manufacturer gains more when involving a higher carbon price. What is more, the retailer will earn no money when the carbon price is too high (i.e., $P_c \geq 0.15$ in the myopic case). This threshold of carbon price in farsighted case is larger than that in myopic case. Therefore, the farsighted behavior is dominant in these parameter settings.

The environmental impact of carbon price is shown in Figure 6, wherein we set carbon price as 0.05, 0.1, and 0.15. This figure demonstrates that the myopic behavior is overall better for the environment than the farsighted one when involving a relatively low-carbon price (i.e., $P_c = 0.05$), whereas the farsighted behavior presents a better environmental performance than the myopic one when involving a relatively high carbon price (i.e., $P_c = 0.1$ and 0.15). In light of the economic and environmental impacts, we can find out that the option of farsighted behavior can not only simultaneously benefit the leading manufacturer and the environment, but also make the following retailer profitable when involving high carbon prices (e.g., $P_c \geq 0.15$). Therefore, the governments can take measures to raise the carbon price for environmental protection.

Finally, the change of profits with different carbon sensitivity coefficients is plotted in Figure 7 to investigate the impact of consumers' low-carbon awareness. In both farsighted and myopic behavior choices, with the increase of this awareness, the manufacturer's earnings increase, whereas the retailer's earnings decrease. This trend is similar to that under the impact of carbon price. However, we find that there exists a threshold of carbon sensitivity coefficient (i.e., $\theta = 1.5$). If $\theta < 1.5$, the myopic manufacturer gains more profit that farsighted one, although its profit gap between two behaviors is not large. The retailer prefers to cooperate with a farsighted manufacturer and the retailer's profit gap between two behaviors is larger than manufacturer's gap. Therefore, adopting a farsighted behavior benefits the entire supply chain.

The impacts of carbon sensitivity coefficient on environment in farsighted and myopic cases present an opposite trend, as shown in Figure 8. A high value of this coefficient leads to a high level of environmental impact in the farsighted case, whereas it leads to a low level of environmental impact in the myopic one. This is because as the value of this coefficient

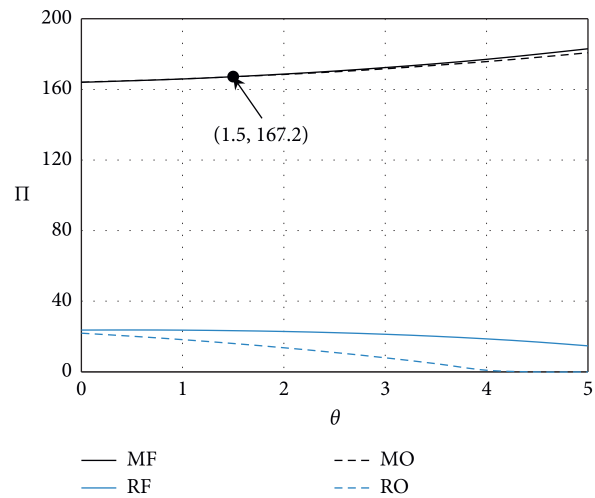

FIGURE 7: Impact of carbon sensitivity coefficient on profits in farsighted and myopic cases.

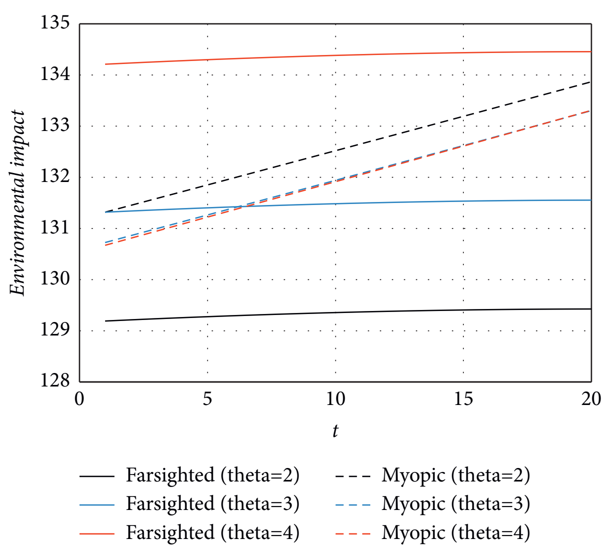

FIGURE 8: Impact of carbon sensitivity coefficient on environment.

increases, the order quantity and the effort of emission reduction also increase. However, the manufacturer exerts more effort in myopic case than that in farsighted one. This effort can offset the impact of order increment and thus play the key role in environmental performance in myopic case. On the contrary, order quantity plays the key role in environmental impact of carbon sensitivity coefficient. Moreover, the gaps between these curves exhibit that the environmental impact of this coefficient in the farsighted case is larger than that in the myopic case. In comparison with the economic impact, we find that the increase of consumers' sensitivity to low-carbon products cannot simultaneously benefit the supply chain and environment in farsighted behavior.

6. Conclusions

This paper considers the decision-making problem of a low-carbon supply chain consisting of a manufacturer and a capital-constrained retailer. By establishing Stackelberg differential game model, manufacturer's optimal strategies of emission reduction and wholesale price and retailer's optimal strategy of order quantity are obtained in the manufacturer's farsighted and myopic behavior choices, respectively. Then, the influence of several key parameters on supply chain performance is analyzed by numerical examples in terms of economic and environmental impacts. From these analyses, the main findings and correlative managerial insights can be summarized as follows.

In a perfectly competitive banking market, the capital constrains have no effect on retailer's decision-makings. The retailer can determine its order quantity as the same as it is fully funded. In both behaviors, we find that the manufacturer will exert increasing effort over time. This result is mainly due to the cost saving by learning-by-doing. Thus, the manufacturer should emphasize the experience accumulation in the production process. This accumulation can help the manufacturer obtain additional fund from cost saving, thereby presenting an extra flexibility in decision-makings.

As the initial value of unit production cost increases, the profits of the manufacturer and retailer decrease in both behaviors. Moreover, the behavior choice presents a heavier effect on the retailer than that on the manufacturer. When involving a high unit production cost, the retailer earns no money. And the cost threshold of the corresponding profit turning point is higher in the farsighted behavior than in the myopic one. These findings indicate that the manufacturer can bear a relatively high unit production cost and simultaneously make the retailer profitable when adopting a farsighted behavior choice. Therefore, the farsighted behavior can enhance the stability and sustainability of the supply chain when facing cost fluctuation.

As the carbon price increases, the manufacturer's profit increases, whereas the retailer's profit and the environmental impact decrease. These findings indicate that a high carbon price benefits the manufacturer and the environment, although it harms the retailer's profit. The manufacturer can transfer this negative effect to the retailer via pricing tool. Moreover, a relatively high carbon price can enhance the manufacturer's preference to the farsighted behavior, which results in a higher profit of the retailer when compared with the myopic behavior. Thus, governments can take measures to raise the carbon price for environmental protection.

As consumers' low-carbon awareness increases, the manufacturer's earnings increase, whereas the retailer's earnings decrease. If this awareness is very low, a myopic manufacturer performs better than a farsighted one, whereas the retailer and the entire supply chain prefer the farsighted manufacturer; otherwise, both the manufacturer and retailer prefer the farsighted behavior, and the increment of this awareness cannot simultaneously benefit the supply chain and environment in farsighted behavior. These findings indicate that consumers must suffer from the environmental impact that results from the additional order although they present an increased low-carbon awareness.

This study can be extended to several promising aspects. First, the assumption of perfectly competitive banking market can be replaced to imperfect competition. Thus, the decision-making of financial institutions is worthy of further investigation. Second, our study only examines the financing scheme from external institutions, i.e., banks. In future, supply chain internal financing in a dynamic setting would be a fruitful venture. Third, we use a traditional supply chain structure wherein the manufacturer is the leader and the retailer is the follower. Other structures, e.g., the retailer leads the supply chain and the manufacturer sells products via e-commerce platforms, are interesting and worth studying.

Data Availability

The data that support the findings of this study are available from the corresponding author (Shihao Wan, B20091100850@cityu.mo), upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

Shihao Wan was responsible for conceptualization and methodology; Jiahui Zhang performed formal analysis and investigation; Shihao Wan and Jiahui Zhang prepared the original draft; Shihao Wan, Jiahui Zhang, and Xianxue Cheng reviewed and edited the manuscript.

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