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Research Article

Myopic versus Farsighted Behaviors in a Low-Carbon Supply Chain with Reference Emission Effects

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The increased carbon emissions cause relatively climate deterioration and attract more attention of governments, consumers, and enterprises to the low-carbon manufacturing. This paper considers a dynamic supply chain, which is composed of a manufacturer and a retailer, in the presence of the cap-and-trade regulation and the consumers' reference emission effects. To investigate the manufacturer's behavior choice and its impacts on the emission reduction and pricing strategies together with the profits of both the channel members, we develop a Stackelberg differential game model in which the manufacturer acts in both myopic and farsighted manners. By comparing the equilibrium strategies, it can be found that the farsighted manufacturer always prefers to keep a lower level of emission reduction. When the emission permit price is relatively high, the wholesale/retail price is lower if the manufacturer is myopic and hence benefits consumers. In addition, there exists a dilemma that the manufacturer is willing to act in a farsighted manner but the retailer looks forward to a partnership with the myopic manufacturer. For a relatively high price of emission permit, adopting myopic strategies results in a better performance of the whole supply chain.

1. Introduction

With the increase of the carbon emissions and the relative deterioration of the climate, consumers are now very concerned about the environmental protection. As early as in 2002, more than 27% of the consumers in OECD countries can be considered as "green consumers", who have strong willingness to buy environmentally friendly products even for costing a little more, while the proportion of the European green consumers is 75% in 2008 compared to 31% in 2005 [1]. Such consumer environmental awareness has a great impact on the product demand [2] and hence promotes the emission reduction in the industry [3, 4]. To provide information for customers, some carbon labelling schemes are established. For example, CO_2 measured label and reducing CO_2 label are issued by Carbon Trust Authority in 2006 [5]. CO_2 measured label can accurately measure the carbon footprint of a product. Reducing CO_2 label also demonstrates a manufacturer's commitment of carbon footprint reduction. These labelling schemes ensure customers to choose green products.

Meanwhile, for mitigating the negative impact of climate change and achieving the sustainable development, most of governments all over the world tend to implement some regulations to reduce the carbon emissions. For instance, as early as in 2005, the first emission trading system is set up by European Union [6], followed by the United States, Canada, Japan, China, and other countries subsequently [7–9]. They have adopted the cap-and-trade regulation to suppress the increase of carbon emissions. This regulation is widely adopted, since it achieves the goal of emission reduction by means of both the regulation and the market and hence can reduce the emission effectively without increasing the policy costs significantly [10]. Under the cap-and-trade regulation, a manufacturing enterprise is allocated a quota called "the carbon cap" by the government. If the actual amount of the emissions is more (conversely, less) than the quota, the manufacturer can buy (conversely, sell) the emission permits through the emission permit market. In modern industry, the manufacturing is inseparable from energy consumption and carbon emissions. Thus, the cap-and-trade regulation has an important impact on the operations management of the manufacturer and even the whole supply chain, when the consumer environmental awareness is considered. Therefore, under the dual influence of the regulation and the market, the supply chain is encouraged to reduce its carbon emissions [11].

In principle, a decision-maker should adopt farsighted strategies, which are concentrated on the long-term interests. However, he/she sometimes needs to act as myopia to focus on short-term profit, especially in a complex business environment [12]. In the context of a dynamic supply chain, because of the power inequality between the members, the leader always makes a decision in a farsighted way and the follower maybe chooses myopia. Hence, there exists a prisoner's dilemma on the supply chain members' behavioral choices [13]. For exploring the reason, many researches investigate the effects of myopia on marketing strategies (i.e., pricing and advertising) and performance of the supply chain members [14–17]. In recent years, the impacts of myopic behavior on operations strategies, such as quality design and production level, catch some attentions [18–21]. However, this effect on emission decision is lacking. Some recent researches make use of the technological innovation to study the behaviors in green supply chain and describe the dynamic environment by the cost learning effect [22] or the technology attenuation effect [23, 24]. Instead, the evolution of "reference emissions" is employed in this paper.

Reference emissions are the consumers' perceived amount of emissions and formed over time based on some information. When consumers make a purchase decision, they usually use the reference emissions to compare with the current emissions from manufacturing unit product at first. This effect of reference emissions is similar to the reference price [25] and the reference quality [26], which also play a critical role in the impact on the market demand. In this paper, we investigate how the supply chain members' myopic behavior affects the relationship between price and emissions in the supply chain consisting of a manufacturer and a retailer. Therefore, this work plans to complement the previous researches by the integration of the consumers' reference emissions, the manufacturer's farsighted and myopic behaviors, and the cap-and-trade regulation in a dynamic framework. Three key questions are addressed in this paper as follows.

(i) When the manufacturer acts in the farsighted or myopic manner with the dynamics of reference emissions, what are the equilibrium emission reduction level, wholesale, and retail prices? What are the comparison results between two behavioral manners?

(ii) How does the manufacturer's behavioral choice affect the relationship of the price and the emissions? How does the cap-and-trade regulation affect the behavior choice?

(iii) Which behavior is the better choice of the manufacturer, and which manner the manufacturer acts does the retailer prefer? When their choices are inconsistent, how to solve this dilemma?

To answer the above questions, we establish a differential game in a bilateral monopoly supply chain, in which the manufacturer acts as a leader and determines the emission reduction level and the wholesale price, and the retailer is a follower and makes a decision on the retail price. Therefore, they play a Stackelberg game and the manufacturer has two behavioral choices, to be farsighted or to be myopic. Solving both the behavior scenarios and comparing them yield some interesting results, which can conclude important managerial insights.

The remainder of this paper is organized as follows. In Section 2, we give a review of the related literature. In Section 3, we establish a differential game model with the dynamics of reference emissions under the cap-and-trade regulation. Section 4 is concerned with deriving equilibrium strategies in both farsighted and myopic scenarios. In Section 5, the strategy choices and their impacts on profits are analyzed. Finally, conclusions, our research limitations, and future directions are summarized in Section 6.

2. Literature Review

This work is mainly related to three areas of researches in the supply chain: consumers' emission-sensitive demand and government's cap-and-trade regulation, myopic behavior in the dynamic marketing and operations environments, and reference effects in the behavioral research.

Consumers' environmental awareness represents the market power and hence has an internal driving effect on the emission reduction of enterprises. Researchers describe the emission-sensitive market by introducing the emissions as a demand suppression factor in the market demand function [27]. Ma et al. [28] analyze the impact of different emission-sensitive coefficients on manufacturer's profits. The authors find that although the emission reduction costs more for the manufacturer, it also stimulates the demand function. Therefore, the participants in the supply chain should coordinate two objectives: the emission reduction and the profit-seeking. Sometimes, the emission reduction and the profit of the supply chain increase simultaneously [29]. Under the cap-and-trade regulation, the carbon quota and the emission permit price affect the decision-making of the manufacturer significantly [30]. Thus, many researches are concentrated on this problem, such as the impacts of production efficiency [31], two rival manufacturers' competition strategy [32], and two products' production and pricing strategies [33]. Compared with the above works, our main contribution is that we study the emission reduction of the supply chain in a differential game framework and analyze the behavioral choice in the dynamic environment.

In the context of dynamic supply chain, more and more researches focus on the impact of myopia on the decisions. In some scenarios, the manufacturer performs better when cooperating with a farsighted retailer, and there are also other scenarios in which the manufacturer performs better with a myopic retailer [34]. Taking the manufacturer's behavioral choice into consideration, Zhang et al. [35] conclude that if the manufacturer prices dynamically, it will gain more than to be myopia. What is more, the supply chain efficiency is the lowest when both the players act as a farsighted manner, and it is the highest when only the retailer chooses to be farsighted. Considering sticky prices, Liu et al. [13] show that the behavioral choices in the supply chain always come to a prisoner's dilemma: farsightedness is a better choice for either of the members, but for both to act myopically makes the whole supply chain better off. In addition, a revenue sharing contract is introduced by the authors to mitigate the adverse impacts. Other recent literature related to the myopic behavior in the supply chain can be found in [16, 20, 26, 36]. The difference between our paper and the above is that the emission reduction decision and pricing strategies are integrated, and the influence of the manufacturer's choice of myopic behavior on the emission-price relationship is also investigated here.

In the dynamic environment, most researches use the reference price effects to describe the dynamics when the pricing strategies are studied in supply chains [14, 16, 23, 25, 37, 38]. Then, to determine the quality decision in the dynamic supply chain, the concept of reference quality is introduced to depict the dynamics. For instance, Gavious and Lowengart [18] consider the effects of the reference price and the reference quality simultaneously and find that the existence of the reference quality effects leads to higher price and quality of the product in the steady state when compared to those strategies without reference effects. In the same dynamic setting, He et al. [39] propose a total cost-sharing contract and prove it to be effective in the whole supply chain. Another research by Liu et al. [26] only focuses on the reference quality effects under a revenue sharing contract, and the findings display that the myopic behavior of the manufacturer results in a higher quality-price ratio which is beneficial to the consumers. Two other similar studies are [36, 40], the former of which considers a closed-loop supply chain. Different from the price/quality reference in the above papers, we propose the concept of "reference emissions" to describe the dynamics in the supply chain.

3. Model Development

We consider a bilateral monopoly supply chain consisting of one manufacturer and one retailer, denoted by the subscripts "m" and "r", respectively. The sequence of events is as follows. The manufacturer first produces one featured product with a certain emission reduction level $\tau(t)$ and announces the wholesale price $w(t)$, and the retailer in response determines the retail price $p(t)$ over time t. A Stackelberg differential game is thus played between the manufacturer and the retailer with the manufacturer as a leader and the retailer following its decisions on emission reduction level and wholesale price to control the retail price over time. In this system, the emission reduction level can be considered as an operational tool, while the price strategy can be considered as a marketing tool. The manufacturer pursuits its own profits by both operational and marketing tools, whereas the retailer only uses the marketing tool to optimize its gains.

The emissions of the product are assumed to be observable after the production is completed, since nowadays it has moved on to concentrate the emissions [41] in the production process and many carbon labelling schemes have been established [5]. When consumers prepare to purchase this product, they can evaluate the emissions for manufacturing the product based on a benchmark, which is called reference emissions. It is the perceived amount of emissions that is formed over time utilizing the consumers' information, such as past emission levels, consumers' previous experience on this product, and so on. Following the method that has been used in [16, 42] to depict the reference price effects and [26, 36] to depict the reference quality effects, we employ an exponential smoothing process of this historical emissions to model the dynamics of reference emissions as follows:

$$\begin{aligned}\dot{R}(t) &= \theta((1-\tau(t))E - R(t)),\\ R(0) &= R_0 \geq 0,\end{aligned} \tag{1}$$

where $R(t)$ and E denote the reference emissions and initial emissions of unit product, respectively. Then, the item $(1-\tau(t))E$ represents the actual emissions when the emission reduction level $\tau(t)$ is implemented. It is obvious that $\tau(t)$ should belong to the interval $[0,1)$ to keep practical. The parameter θ is the memory parameter, which should be positive and continuous, and R_0 represents the initial reference emissions at time $t=0$.

Similar to previous literature [18, 26, 36] that describe the reference price/quality, we assume that the market demand is affected by reference emissions as well as market capacity, retail price, and emissions. The influence of reference emissions is related to the gap between actual emissions and reference emissions. Hence, the function of market demand is given by

$$\begin{aligned}D(p(t),\tau(t),R(t)) = \alpha - \beta p(t) - \gamma_1(1-\tau(t))E\\ - \gamma_2((1-\tau(t))E - R(t)),\end{aligned} \tag{2}$$

where $\alpha > 0$ represents the market capacity, $\beta > 0$ and $\gamma_1 > 0$ reflect the effects of retail price and emissions on current demand, respectively, and $\gamma_2 > 0$ captures the reference emission effects. A higher $\gamma_2 > 0$ means that consumers are more sensitive to the gap between the actual emissions and the reference emissions, and $\gamma_2 = 0$ means no reference effect exists. This specification for demand function is derived from the classic linear demand function $D(p) = \alpha - \beta p$, combined with the emission effect which is widely used in the literature such as [1, 20, 43].

The total costs of the supply chain consist of the manufacturing cost, the emission reduction cost, and the emission cost. Let c denote the unit manufacturing cost and $C(\tau(t))$ denote the emission reduction cost. In accordance with the former literature [44–46], a quadratic cost function about emission reduction level is used as follows:

$$C(\tau(t)) = \frac{k}{2}\tau^2(t), \tag{3}$$

where k represents the cost coefficient of emission reduction. Increasing marginal mitigation cost means that the manufacturer has to spend more to further reduce emissions when it has been in a high level of emission reduction.

The emission cost is considered in an emission permits trading scheme. The manufacturer is allocated a certain quantity of emission permits for each time point, named as initial quota E_0. If the amount of manufacturer's emission is not equal to the emission quota, the manufacturer can trade the emission permits in the emission permit market. For instance, the manufacturer has to buy the emission permits with the price of S, if the total emissions, $E(1-\tau(t))D(p(t),\tau(t),R(t))$, exceed the quota. Conversely, if $E(1-\tau(t))D(p(t),\tau(t),R(t)) < E_0$, the manufacturer can sell the surplus of the emission permits. Note that the above way to express the cost/revenue from the trade of the emission permits is commonly used in the literature [47–49]. In the following discussions, we assume $\alpha-\beta(c+SE)-\gamma_1 E>0$ to ensure that the demand is positive.

When an infinite time horizon is assumed, the objective functionals of both players are given by

$$J_m = \int_0^\infty e^{-\rho t}\Big((w(t)-c)\,D(p(t),\tau(t),R(t)) - S\big(E(1-\tau(t))\,D(p(t),\tau(t),R(t))-E_0\big) - C(\tau(t))\Big)\,dt, \tag{4}$$

$$J_r = \int_0^\infty e^{-\rho t}\,(p(t)-w(t))\,D(p(t),\tau(t),R(t))\,dt, \tag{5}$$

where ρ is a positive discount rate.

Thus, taking the above dynamic relationships, (1)-(5), together, a differential game between the manufacture and the retailer in the emission permits trading scheme is developed as follows:

$$\max_{w(\cdot),\tau(\cdot)} \int_0^\infty e^{-\rho t}\Big((w(t)-c-SE(1-\tau(t)))(\alpha-\beta p(t) - \gamma_1(1-\tau(t))E - \gamma_2((1-\tau(t))E-R(t))) - \frac{k}{2}\tau^2(t) + SE_0\Big)\,dt, \tag{6a}$$

$$\max_{p(\cdot)} \int_0^\infty e^{-\rho t}\,(p(t)-w(t))(\alpha-\beta p(t)-\gamma_1(1-\tau(t))E - \gamma_2((1-\tau(t))E-R(t)))\,dt, \tag{6b}$$

$$\text{s.t.}\quad \dot{R}(t) = \theta((1-\tau(t))E-R(t)),\quad R(0)=R_0. \tag{6c}$$

In (6a), (6b), and (6c), we depict a Stackelberg differential game with two players, three control variables, $w(t)$, $\tau(t)$, and $p(t)$, as well as one state variable $R(t)$. In common, the players' strategies should be stationary in the infinite time horizon game [50]. This assumption will be used in the following section for model solving.

4. Farsighted and Myopic Solutions

In a farsighted scenario, both the members of the supply chain consider the impact of their behaviors on their current profits and the streams of future profits simultaneously. In contrast, when the channel members act as a myopic behavior, they only maximize their current profits and ignore the future influence of their decision-making on the evolution of the state dynamics. These two scenarios are successively considered in Sections 4.1 and 4.2. Since the manufacturer is the leader in the Stackelberg differential games, and its behaviors affect the equilibrium strategies significantly, we will get the feedback equilibrium solutions in farsighted and myopic scenarios, respectively.

From (6a), (6b), and (6c), we find that the retail price is absent in the dynamics of (6c). It means that the retailer's behavior choice has no influence on the decision for retail price. Thus, the equilibrium retail price can be obtained from the following optimization problem in (7) firstly.

$$\max_p\{(p-w)(\alpha-\beta p-\gamma_1(1-\tau)E-\gamma_2((1-\tau)E-R))\}. \tag{7}$$

Thus, the pricing reaction function of the retailer is given by

$$p(\tau,w,R) = \frac{\gamma_2}{2\beta}R + \frac{\alpha+\beta w-(\gamma_1+\gamma_2)E(1-\tau)}{2\beta}. \tag{8}$$

Equation (8) implies that the retail price is positively related with the wholesale price, the emission reduction level, and the reference emissions.

4.1. Farsighted Scenario. The farsighted scenario means that the manufacturer adopts farsighted strategies and takes full account of the impacts of its decision-making on the dynamics of reference emissions. Let the superscript "F" signify the "Farsighted" scenario, and let V_r^F and V_m^F denote the value functions of the retailer and the manufacturer, respectively. We assume that the retailer's decision on the retail price shown in (8) is known in order to get the feedback equilibrium strategies. Then, substituting (8) into the objectives of (6a), (6b), and (6c), the Hamiltonian-Jacobi-Bellman (HJB) equations of both players can be established as follows:

$$\rho V_r^F = \frac{1}{\beta}\left(\frac{\alpha}{2}-\frac{\beta}{2}w+\frac{\gamma_2}{2}R-\frac{(\gamma_1+\gamma_2)E}{2}(1-\tau)\right)^2 + \frac{\partial V_r^F}{\partial R}\theta((1-\tau)E-R), \tag{9}$$

$$\rho V_m^F = \max_{\tau,w}\left\{(w-c-SE(1-\tau))\cdot\left(\frac{\alpha}{2}-\frac{\beta}{2}w+\frac{\gamma_2}{2}R-\frac{(\gamma_1+\gamma_2)E}{2}(1-\tau)\right)-\frac{k}{2}\tau^2 + SE_0 + \frac{\partial V_m^F}{\partial R}\theta((1-\tau)E-R)\right\}. \tag{10}$$

We define the following notations to simplify the expression of the model:

$$a_1 \equiv (\beta S + \gamma_1 + \gamma_2) E, \tag{11}$$

$$a_2 \equiv 4\beta k - a_1^2, \tag{12}$$

$$a_3 \equiv \alpha - \beta c - a_1, \tag{13}$$

$$a_4 \equiv \gamma_2 E a_1 + a_2, \tag{14}$$

$$\Delta \equiv \sqrt{(\rho a_2 + 2\theta a_4)^2 - 16\beta\theta^2 E^2 k \gamma_2^2}, \tag{15}$$

$$a_5 \equiv \rho a_2 + 2\theta a_4 - \Delta, \tag{16}$$

$$a_6 \equiv (a_2 - a_1 a_3)(\rho a_2 + \theta a_4) + 4\beta\theta E k \gamma_2 a_3. \tag{17}$$

The parameter constraint $a_2 > 0$ is needed to guarantee that the right side of (10) is concave in (τ, w) and hence the maximum exists. We depict the equilibrium emission reduction level, wholesale price, and retail price as functions of reference emissions R and obtain the value functions of the manufacturer and the retailer in Proposition 1. The proof for this proposition and subsequent ones, as well as the corollaries, are given in Appendix A.

Proposition 1. *In the farsighted scenario, the feedback equilibrium emission reduction level, wholesale price, and retail price are given by*

$$\tau^F = 1 - \frac{a_5 - 2\gamma_2\theta E a_1}{2\theta E a_2} R - \frac{2a_6}{a_2(\Delta + \rho a_2)}, \tag{18}$$

$$w^F = \left(\frac{a_5(a_1 - 2\gamma_1 E - 2\gamma_2 E)}{4\beta\theta E a_2} - \frac{\gamma_2(SEa_1 - 2k)}{a_2}\right) R + \frac{\alpha + \beta c}{2\beta} + \frac{2a_6(a_1 - 2\gamma_1 E - 2\gamma_2 E)}{2\beta a_2(\Delta + \rho a_2)}, \tag{19}$$

$$p^F = \left(\frac{a_5(a_1 - 4\gamma_1 E - 4\gamma_2 E)}{8\beta\theta E a_2} - \frac{\gamma_2(SEa_1 - 3k)}{a_2}\right) R + \frac{3\alpha + \beta c}{4\beta} + \frac{2a_6(a_1 - 4\gamma_1 E - 4\gamma_2 E)}{4\beta a_2(\Delta + \rho a_2)}, \tag{20}$$

and the value functions for the manufacturer and the retailer are given by

$$V_m^F(R) = \frac{a_5}{16\beta\theta^2 E^2} R^2 + \frac{a_5(a_2 - a_1 a_3) + 8\beta\theta E k\gamma_2 a_3}{4\beta\theta E(\Delta + \rho a_2)} R + \frac{SE_0}{\rho} + \frac{k a_3^2}{2\rho a_2} + \frac{(a_2 - a_1 a_3)(a_5(a_2 - a_1 a_3) + 8\beta\theta E k \gamma_2 a_3)}{4\rho\beta a_2(\Delta + \rho a_2)} + \frac{(a_5(a_2 - a_1 a_3) + 8\beta\theta E k\gamma_2 a_3)^2}{8\rho\beta a_2(\Delta + \rho a_2)^2}, \tag{21}$$

$$V_r^F(R) = \frac{(a_1 a_5 - 8\beta\theta E k\gamma_2)^2}{64\beta\theta^2 E^2 a_2 \Delta} R^2 + \frac{(a_1 a_5 - 8\beta\theta E k \gamma_2)}{2\beta\theta E(\Delta + \rho a_2)} \cdot \left(\frac{a_6(2a_1\Delta + a_1 a_5 - 8\beta\theta E k\gamma_2)}{4a_2\Delta(\Delta + \rho a_2)} - \frac{\alpha - \beta c}{4}\right) R + \frac{1}{\rho\beta}\left(\frac{\alpha - \beta c}{4} - \frac{2a_1 a_6}{4a_2(\Delta + \rho a_2)}\right)^2 + \frac{a_6(a_1 a_5 - 8\beta\theta E k\gamma_2)}{\rho\beta a_2(\Delta + \rho a_2)^2} \cdot \left(\frac{a_6(2a_1\Delta + a_1 a_5 - 8\beta\theta E k\gamma_2)}{4a_2\Delta(\Delta + \rho a_2)} - \frac{\alpha - \beta c}{4}\right). \tag{22}$$

From Proposition 1, we know that the equilibrium emission reduction level, wholesale price, and retail price are linear with respect to the reference emissions. Moreover, the value functions of both players are convex in the reference emissions. That is to say, the reference emissions have the increasing marginal contribution to both players' profits. Note that the carbon quota exists only in (21). This implies that carbon quota does not affect the retailer's profit and the decisions of emission reduction level, wholesale price, and retail price. The government should allocate sufficient carbon quota to ensure profitability of the manufacturer.

Substitute the equilibrium emission reduction level, i.e., (18), into (6c). Then, we get a differential equation. Solving this equation and using Proposition 1, we have Proposition 2 as follows.

Proposition 2. *In the farsighted scenario, the trajectories for the equilibrium emission reduction level, wholesale price, and retail price are given by*

$$\tau^F(t) = \frac{2\gamma_2\theta E a_1 - a_5}{2\theta E a_2}\left(R_0 - R_\infty^F\right) e^{-\delta^F t} + \tau_\infty^F, \tag{23}$$

$$w^F(t) = \left(\frac{a_5(a_1 - 2\gamma_1 E - 2\gamma_2 E)}{4\beta\theta E a_2} - \frac{\gamma_2(SEa_1 - 2k)}{a_2}\right) \cdot \left(R_0 - R_\infty^F\right) e^{-\delta^F t} + w_\infty^F, \tag{24}$$

$$p^F(t) = \left(\frac{a_5(a_1 - 4\gamma_1 E - 4\gamma_2 E)}{8\beta\theta E a_2} - \frac{\gamma_2(SEa_1 - 3k)}{a_2}\right) \cdot \left(R_0 - R_\infty^F\right) e^{-\delta^F t} + p_\infty^F, \tag{25}$$

and the trajectories for the reference emissions and the demand are given by

$$R^F(t) = \left(R_0 - R_\infty^F\right) e^{-\delta^F t} + R_\infty^F, \tag{26}$$

$$D^F(t) = \left(\frac{\gamma_2 \beta k}{a_2} - \frac{a_1 a_5}{8\theta E a_2}\right)\left(R_0 - R_\infty^F\right) e^{-\delta^F t} + D_\infty^F, \tag{27}$$

where

$$\delta^F = \frac{\Delta - \rho a_2}{2a_2}, \quad (28)$$

$$R_\infty^F = \frac{4\theta E a_6}{\Delta^2 - \rho^2 a_2^2}, \quad (29)$$

$$\tau_\infty^F = 1 - \frac{4\theta a_6}{\Delta^2 - \rho^2 a_2^2}, \quad (30)$$

$$w_\infty^F = \frac{\alpha + \beta c}{2\beta} + \frac{2\theta E a_6 (\beta S - \gamma_1)}{\beta(\Delta^2 - \rho^2 a_2^2)}, \quad (31)$$

$$p_\infty^F = \frac{3\alpha + \beta c}{4\beta} + \frac{\theta E a_6 (\beta S - 3\gamma_1)}{\beta(\Delta^2 - \rho^2 a_2^2)}, \quad (32)$$

$$D_\infty^F = \frac{\alpha - \beta c}{4} - \frac{\theta E a_6 (\beta S + \gamma_1)}{\Delta^2 - \rho^2 a_2^2}. \quad (33)$$

From Proposition 2, we find that if $\delta^F > 0$, the emission reduction level $\tau^F(t)$, the prices $w^F(t)$, $p^F(t)$, the reference emissions $R^F(t)$, and the demand $D^F(t)$ can converge to their steady states τ_∞^F, w_∞^F, p_∞^F, R_∞^F, and D_∞^F, respectively, when $t \longrightarrow +\infty$. Here, we have to emphasize that the steady-state reference emissions are equal to the steady-state emissions of unit product. Moreover, denote $A_1 \equiv (a_5(a_1 - 4\gamma_1 E - 4\gamma_2 E)/8\beta\theta E a_2 - \gamma_2(SEa_1 - 3k)/a_2)$ and $A_2 \equiv (a_5(a_1 - 2\gamma_1 E - 2\gamma_2 E)/4\beta\theta E a_2 - \gamma_2(SEa_1 - 2k)/a_2)$. Then, from Proposition 2, according to the size relationship of the initial reference emissions R_0 and the steady-state emissions R_∞^F, as well as other parameters, both supply chain members can choose penetration or skimming strategy. The following corollary describes the corresponding results.

Corollary 3. *On the basis of initial reference emission R_0, the steady-state emission R_∞^F, and the items A_1 and A_2, we provide the pricing and emission strategies as follows:*

(i) *when $A_2(R_0 - R_\infty^F) > 0$, the farsighted manufacturer leads to the skimming pricing strategy; when $A_2(R_0 - R_\infty^F) < 0$, the farsighted manufacturer leads to the penetration pricing strategy;*

(ii) *when $A_1(R_0 - R_\infty^F) > 0$, the farsighted retailer leads to the skimming pricing strategy; when $A_1(R_0 - R_\infty^F) < 0$, the farsighted retailer leads to the penetration pricing strategy;*

(iii) *when $(2\gamma_2\theta E a_1 - a_5)(R_0 - R_\infty^F) > 0$, the farsighted manufacturer leads to the penetration emission strategy, i.e., the emission reduction level decreases over time; when $(2\gamma_2\theta E a_1 - a_5)(R_0 - R_\infty^F) < 0$, the farsighted manufacturer leads to the skimming emission strategy; i.e., the emission reduction level increases over time.*

Corollary 3 shows that the retailer adopts the same pricing strategy as the manufacturer if $A_1 A_2 > 0$, while if $A_1 A_2 < 0$, the retailer implements the opposite pricing strategy. When $2\gamma_2\theta E a_1 - a_5 < 0$, the manufacturer adopts a high emission level initially and then gradually reduces the emissions if consumers have a high enough reference emission. The reason is that $2\gamma_2\theta E a_1 - a_5 < 0$ implies the reference effect plays a major role, and a farsighted manufacturer can trace the consumers' emission-learning process. When $2\gamma_2\theta E a_1 - a_5 > 0$, price, emissions, and costs mainly affect the emission reduction strategy and the manufacturer ignores the reference effect.

In Corollary 4, we report the comparative static results for the steady-strategies, the reference emissions, and the demand on the key parameters ρ, γ_2, θ, and k in the farsighted scenario. We find that the parameters ρ and γ_2 versus θ and k have the opposite effects. Taking the emission reduction level as an example, the steady-state value is rising with the increase of discount rate ρ and reference emission parameter γ_2, and falling with the increase of memory parameter θ and the cost parameter of emission reduction k. This means that when consumers are more sensitive to the emission difference between the actual emissions and preference emissions or hold better emission memory, or the manufacturer holds less patience, or emission reduction costs less, the manufacturer makes choice of a higher emission reduction level. Meanwhile, the emissions of unit product are lower and the demand is larger. Furthermore, there exists a threshold of the carbon price for both the prices, respectively. When the manufacturer/retailer faces a lower carbon price, i.e., $S < \gamma_1/\beta$ for the manufacturer or $S < 3(\gamma_1/\beta)$ for the retailer, the price has the same trends as the emission reduction level. On the contrary, when the carbon price is higher, both the players' determined prices have the opposite trends. That is because the marketing tools play a major role on players' profits, since we can rewrite the inequalities as $\beta > \gamma_1/S$ and $\beta > 3(\gamma_1/S)$. Moreover, the carbon price appears only in the manufacturer's value function. This implies that the carbon price affects the manufacturer directly and affects the retailer indirectly through the wholesale price. Thus, the threshold for the retail price is larger than that for the wholesale price.

Corollary 4. *In the farsighted scenario, the comparative static analyses for the steady-state strategies are summarized in Table 1.*

4.2. Myopic Scenario. The myopic scenario means that the manufacturer disregards the influence on the dynamics of reference emission and pays attention to the current profits when making decisions on the emission reduction and the wholesale price. In this scenario, the optimal control problem is reduced to such a static optimization problem at each time point as follows:

$$\max_{w,\tau} \quad (w - c - SE(1-\tau))(\alpha - \beta p - \gamma_1(1-\tau)E - \gamma_2((1-\tau)E - R)) - \frac{1}{2}k\tau^2 + SE_0, \quad (34a)$$

$$\text{s.t.} \quad \dot{R} = \theta((1-\tau)E - R). \quad (34b)$$

The superscript "M" is used to signify "Myopic scenario". Then, the equilibrium results are presented as follows, when the manufacturer is myopic.

Table 1: Comparative static results for the farsighted scenario.

Parameters	R_∞^F	τ_∞^F	w_∞^F $S<\frac{\gamma_1}{\beta}$	w_∞^F $S>\frac{\gamma_1}{\beta}$	p_∞^F $S<3\frac{\gamma_1}{\beta}$	p_∞^F $S>3\frac{\gamma_1}{\beta}$	D_∞^F
ρ	↓	↑	↑	↓	↑	↓	↑
γ_2	↓	↑	↑	↓	↑	↓	↑
θ	↑	↓	↓	↑	↓	↑	↓
k	↑	↓	↓	↑	↓	↑	↓

Note: ↑, increase; ↓, decrease.

Proposition 5. *In the myopic scenario, the trajectories for the equilibrium emission reduction level, wholesale price, and retail price are given by*

$$\tau^M(t) = \frac{\gamma_2 a_1}{a_2}\left(R_0 - R_\infty^M\right)e^{-\delta^M t} + \tau_\infty^M, \tag{35}$$

$$w^M(t) = -\frac{\gamma_2\left(SEa_1 - 2k\right)}{a_2}\left(R_0 - R_\infty^M\right)e^{-\delta^M t} + w_\infty^M, \tag{36}$$

$$p^M(t) = -\frac{\gamma_2\left(SEa_1 - 3k\right)}{a_2}\left(R_0 - R_\infty^M\right)e^{-\delta^M t} + p_\infty^M, \tag{37}$$

the trajectories for the reference emissions and the demand are given by

$$R^M(t) = \left(R_0 - R_\infty^M\right)e^{-\delta^M t} + R_\infty^M, \tag{38}$$

$$D^M(t) = \frac{\beta k\gamma_2}{a_2}\left(R_0 - R_\infty^M\right)e^{-\delta^M t} + D_\infty^M, \tag{39}$$

and the value functions for the manufacturer and the retailer are given by

$$V_m^M(R) = \frac{a_2}{2\beta k}V_r^M(R) + \frac{SE_0}{\rho}, \tag{40}$$

$$\begin{aligned} V_r^M(R) &= \frac{\beta k^2\gamma_2^2}{a_2\left(\rho a_2 + 2\theta a_4\right)}R^2 \\ &+ \frac{2\beta k^2\gamma_2\left(\theta\gamma_2 E\left(a_2 + a_1 a_3\right) + \left(\rho + 2\theta\right)a_2 a_3\right)}{a_2\left(\rho a_2 + \theta a_4\right)\left(\rho a_2 + 2\theta a_4\right)}R + \frac{\beta k^2 a_3^2}{\rho a_2^2} \\ &+ \frac{2\theta E\beta k^2\gamma_2\left(a_2 - a_1 a_3\right)\left(\theta\gamma_2 E\left(a_2 + a_1 a_3\right) + \left(\rho + 2\theta\right)a_2 a_3\right)}{\rho a_2^2\left(\rho a_2 + \theta a_4\right)\left(\rho a_2 + 2\theta a_4\right)}, \end{aligned} \tag{41}$$

where

$$\delta^M = \frac{\theta a_4}{a_2}, \tag{42}$$

$$R_\infty^M = \frac{E\left(a_2 - a_1 a_3\right)}{a_4}, \tag{43}$$

$$\tau_\infty^M = 1 - \frac{\left(a_2 - a_1 a_3\right)}{a_4}, \tag{44}$$

$$w_\infty^M = \frac{\alpha + \beta c}{2\beta} + \frac{\left(a_2 - a_1 a_3\right)\left(\beta S - \gamma_1\right)E}{2\beta a_4}, \tag{45}$$

$$p_\infty^M = \frac{3\alpha + \beta c}{4\beta} + \frac{\left(a_2 - a_1 a_3\right)\left(\beta S - 3\gamma_1\right)E}{4\beta a_4}, \tag{46}$$

$$D_\infty^M = \frac{\beta k\left(\gamma_2 E + a_3\right)}{a_4}. \tag{47}$$

Proposition 5 shows that the trajectories and steady states of myopic scenario are similar to those of farsighted scenario, which are represented in Propositions 1 and 2. Since the manufacturer does not consider the evolution of the reference emissions, the steady states have no relationship with the parameters θ and ρ. From (40), we know that the expression of manufacturer's value function consists of two items. The first item represents the income from the manufacturing and sale of the product, while the second item, which is also included in the farsighted scenario, represents the income from the carbon quota. Thus, the effects of carbon quota on the supply chain's decisions and performance are the same as those in the farsighted scenario. We denote $V_{m,m}^M(R)$ as the first item, i.e., "product profits". Then, the profits of both players in the myopic scenario are compared in Corollary 6.

Corollary 6. *In the myopic scenario, the manufacturer's product profits and the retailer's profits are compared as follows:*

(i) $V_{m,m}^M(R) < V_r^M(R)$, *if* $S > \sqrt{2k}/E\sqrt{\beta} - (\gamma_1+\gamma_2)/\beta$ *holds;*

(ii) $V_{m,m}^M(R) = V_r^M(R)$, *if* $S = \sqrt{2k}/E\sqrt{\beta} - (\gamma_1+\gamma_2)/\beta$ *holds;*

(iii) $V_{m,m}^M(R) > V_r^M(R)$, *if* $S < \sqrt{2k}/E\sqrt{\beta} - (\gamma_1+\gamma_2)/\beta$ *holds.*

From Corollary 6, we obtain a result that the retailer's profits are greater than the manufacturer's product profits when $S > \sqrt{2k}/E\sqrt{\beta} - (\gamma_1+\gamma_2)/\beta$, although the retailer is the follower in the Stackelberg game. What is more interesting, when the emission permit price is relatively high and the emission quota is relatively low, the retailer's profits maybe exceed the manufacturer's total profits. This is because both the influences of carbon emission and price on the market demand are integrated in the model.

We rewrite the inequalities $S > \sqrt{2k}/E\sqrt{\beta} - (\gamma_1+\gamma_2)/\beta$ and $S < \sqrt{2k}/E\sqrt{\beta} - (\gamma_1+\gamma_2)/\beta$ as $S + (\gamma_1+\gamma_2)/\beta > \sqrt{2k}/E\sqrt{\beta}$ and $S + (\gamma_1+\gamma_2)/\beta < \sqrt{2k}/E\sqrt{\beta}$, respectively. Then, the item $S + (\gamma_1+\gamma_2)/\beta$ can be regarded as the "relative value" of the manufacturer's emission reduction, while the item $\sqrt{2k}/E\sqrt{\beta}$

Table 2: Comparative static results for the myopic scenario.

Parameters	R_∞^M	τ_∞^M	w_∞^M		p_∞^M		D_∞^M
			$S < \frac{\gamma_1}{\beta}$	$S > \frac{\gamma_1}{\beta}$	$S < 3\frac{\gamma_1}{\beta}$	$S > 3\frac{\gamma_1}{\beta}$	
γ_2	↓	↑	↑	↓	↑	↓	↑
k	↑	↓	↓	↑	↓	↑	↓

Note: ↑, increase; ↓, decrease.

represents the "relative cost" of the manufacturer's emission reduction. Then, on one hand, for a high relative value and a low relative cost of the emission reduction, the manufacturer opts for a high emission reduction level. This results in the sharply growth of the demand. Thus, the retailer can perform better than the manufacturer. On the other hand, when the relative value of emission reduction is relatively low and the relative cost of emission reduction is relatively high, the manufacturer needs to keep a high wholesale price so as to make up for the cost of emission reduction. Hence, its profits are more than the retailer. Additionally, when the profit item SE_0/ρ is relatively high, the manufacture may always gain more profits than the retailer by means of more efforts on emission reduction and/or the acquisition of high carbon quota.

Denote $A_3 \equiv (\sqrt{(\gamma_1+\gamma_2)^2E^2+8\beta k}-(\gamma_1+\gamma_2)E)/2\beta E$ and $A_4 \equiv (\sqrt{(\gamma_1+\gamma_2)^2E^2+12\beta k}-(\gamma_1+\gamma_2)E)/2\beta E$. Similar to the pricing and emission strategies in the farsighted scenario, the strategies in the myopic scenario are summarized in Corollary 7.

Corollary 7. *On the basis of initial reference emission R_0 and steady-state emission R_∞^M, we provide the pricing and emission strategies as follows.*

(i) *When $R_0 > R_\infty^M$, both the players lead to the skimming pricing strategy if $S < A_3$ holds; the myopic manufacturer leads to the penetration pricing strategy and the myopic retailer leads to the skimming pricing strategy if $A_3 < S < A_4$ holds; both the players lead to the penetration pricing strategy if $S > A_4$ holds.*

(ii) *When $R_0 < R_\infty^M$, both the myopic players lead to the penetration pricing strategy if $S < A_3$ holds; the myopic manufacturer leads to the skimming pricing strategy and the myopic retailer leads to the penetration pricing strategy if $A_3 < S < A_4$ holds; both the players lead to the skimming pricing strategy if $S > A_4$ holds.*

(iii) *When $R_0 > R_\infty^M$, the myopic manufacturer leads to the penetration emission strategy; when $R_0 < R_\infty^M$, the myopic manufacturer leads to the skimming emission strategy.*

Corollary 7 shows that when consumers have a high enough reference emission, the manufacturer sets to a low emission level at the initial time to avoid the negative impact resulting from the ignored influence on the reference emissions. Moreover, if the emission permit price is low enough, i.e., $S < A_3$, the high cost of emission reduction has to be balanced by setting a high price; otherwise, high emission permit price results in some income from the quota saving and hence the members can set a low price. Since the manufacturer is the leader, it meets a lower threshold than the retailer.

Corollary 8 reports the comparative static results in the myopic scenario. Here, only two key parameters γ_2 and k have effects. They have the same influence as in the farsighted scenario, since when ρ tends to infinity and/or θ tends to zero, all the farsighted strategies reduce to the myopic ones.

Corollary 8. *In the myopic scenario, the comparative static analyses for the steady-state strategies are summarized in Table 2.*

5. Scenario Comparison

In this section, we compare the steady-state strategies between farsighted and myopic scenarios and then analyze the manufacturer's behavior choice through the profit comparison in these two scenarios.

5.1. Strategy Comparisons. In the steady state, the strategies under both the farsighted and the myopic scenarios are compared in Proposition 9.

Proposition 9. *In the steady state, the comparisons of the emission reduction levels and the prices between both scenarios are depicted as follows:*

(i) $\tau_\infty^M > \tau_\infty^F$;

(ii) *$w_\infty^M < w_\infty^F$ if $S > \gamma_1/\beta$ holds, and $w_\infty^M \geq w_\infty^F$ otherwise;*

(iii) *$p_\infty^M < p_\infty^F$ if $S > 3\gamma_1/\beta$ holds, and $p_\infty^M \geq p_\infty^F$ otherwise.*

Proposition 9 implies that, in the steady state, the myopic manufacturer makes greater efforts to reduce emissions than the farsighted one. However, in which scenario the manufacturer/retailer sets higher price depends on the emission permit price. That is to say, when facing a myopic manufacturer, consumers will purchase a relatively low-emission product at a lower price if the emission permit price is higher than $3\gamma_1/\beta$, and at a higher price otherwise. On the contrary, when facing a farsighted manufacturer, consumers will purchase a relatively high-emission and high-price product if the emission permit price is higher than $3\gamma_1/\beta$, and they will purchase a relatively high-emission and low-price product otherwise.

In order to explain this finding, we review some results of strategy comparisons with reference price/quality effects.

Martín-Herrán [16] show, that in the steady state, the equilibrium price is set to be lower by a myopic player than that by a farsighted one. The authors explain that the myopic player disregards the price learning process of the consumers. What is more, the study by Liu et al. [26] finds that, in the presence of reference quality effects, a manufacturer opts for a lower product quality since a higher quality results in a higher reference quality and hence causes a negative impact on the market demand. Similar to the reference quality effects, a lower amount of emissions results in lower reference emissions which also affect the demand negatively. Thus, the farsighted manufacturer sets a lower level of emission reduction according to the dynamics of reference emissions.

Moreover, a higher price is adopted by both the farsighted manufacturer and the corresponding retailer when the emission permit price is especially high, i.e., $S > 3\gamma_1/\beta$. Conversely, a higher price is adopted by both the players in the myopic setting when the emission permit price is especially low, i.e., $S < \gamma_1/\beta$. Otherwise, when $\gamma_1/\beta < S < 3\gamma_1/\beta$, a higher price is used by the farsighted manufacturer and the myopic-setting retailer.

From Proposition 9, we know that the farsighted manufacturer will adopt a high-emission strategy and the farsighted-setting retailer will select a high-price if $S > 3\gamma_1/\beta$ holds, while selecting a low-price if $S < 3\gamma_1/\beta$ holds. However, the myopic manufacturer will take a low-emission strategy and the myopic-setting retailer will select a low-price if $S > 3\gamma_1/\beta$ holds, while selecting a high-price if $S < 3\gamma_1/\beta$ holds. Which strategy benefits the consumers more? To answer this question, we give a definition of "emission-price product", which is the product of the emissions and the price, and then use it in Proposition 10.

Proposition 10. *The steady-state products $R^F_\infty p^F_\infty$ between the farsighted and myopic scenarios are compared as follows:*

(i) $R^M_\infty p^M_\infty < R^F_\infty p^F_\infty$, *if* $((\beta S - 3\gamma_1)/2\beta)R^F_\infty + (3\alpha + \beta c)/4\beta > 0$ *holds;*

(ii) $R^M_\infty p^M_\infty > R^F_\infty p^F_\infty$, *if* $((\beta S - 3\gamma_1)/2\beta)R^F_\infty + (3\alpha + \beta c)/4\beta < 0$ *holds.*

From Proposition 10, we know that there exists a threshold $((\beta S - 3\gamma_1)/2\beta)R^F_\infty + (3\alpha + \beta c)/4\beta$. When the threshold is positive, the consumers can gain more, i.e., lower emission-price product, in the myopic scenario. In other words, when the consumers are less sensitive to the emission and/or the emission permit price is higher, the emission-price product is lower in the myopic scenario. In contrast, when the threshold is negative, the consumers can be benefited from the farsighted setting.

5.2. Behavioral Choice. It depends on the profit comparison between the farsighted and the myopic scenarios that which behavior the manufacturer prefers to choose and which behavior the retailer wants the manufacturer to act. If the manufacturer decides to act as a farsighted manner and the retailer prefers a farsighted cooperator, i.e., $V^F_m > V^M_m$ and $V^F_r > V^M_r$, or the manufacturer as a myopic manner and the retailer prefers a myopic cooperator, i.e., $V^M_m > V^F_m$ and $V^M_r > V^F_r$, they can reach agreement and adopt the corresponding actions. However, if the manufacturer opts for a farsighted behavior and the retailer prefers a myopic cooperator, i.e., $V^F_m > V^M_m$ and $V^M_r > V^F_r$, or the manufacturer acts as a myopic manner and the retailer prefers a farsighted cooperator, i.e., $V^M_m > V^F_m$ and $V^F_r > V^M_r$, either the manufacturer or the retailer will lose profits. To deal with this dilemma, two cooperators have to negotiate a solution, which can be better off for each other.

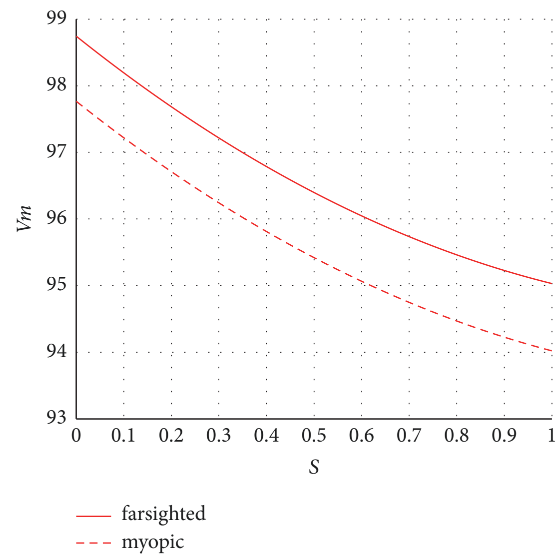

Figure 1: The profits of the manufacturer as S increases.

Intuitively, the manufacturer should make a choice of farsighted behavior to maximize the long-term profits, since it acts as a leader in the supply chain. Meanwhile, its choice will reduce the retailer's profits if the retailer wants a myopic manufacturer. However, is it true?

To make the discussion meaningful and in practice, the control variables and the state variable should satisfy the nonnegative constraints, which we ignore in our calculation. Since it is difficult to obtain an analytical solution by comparison of both scenarios' profits, therefore, we analyze the profits by means of numerical simulations. We set the benchmark values of the parameters, which satisfy the nonnegative constraints, as follows.

(i) Demand parameters: $\alpha = 10, \beta = 1, \gamma_1 = 0.3, \gamma_2 = 0.7$.

(ii) Cost parameters: $c = 1, k = 2$.

(iii) Reference emission parameters: $\theta = 2$.

(iv) Emission parameters: $E_0 = 0.2, E = 0.4, S = 0.5$.

(v) Discount rate: $\rho = 0.1$.

These parameters are set based on previous studies related to the feedback equilibrium strategies of pricing and operations [20, 26]. At first, we analyze the profits of the manufacturer, the retailer, and the whole supply chain (denoted by the subscript "sc") as the emission permit price changes. The results in both scenarios are plotted in Figures 1–3. As the intuition discussed above, the manufacturer

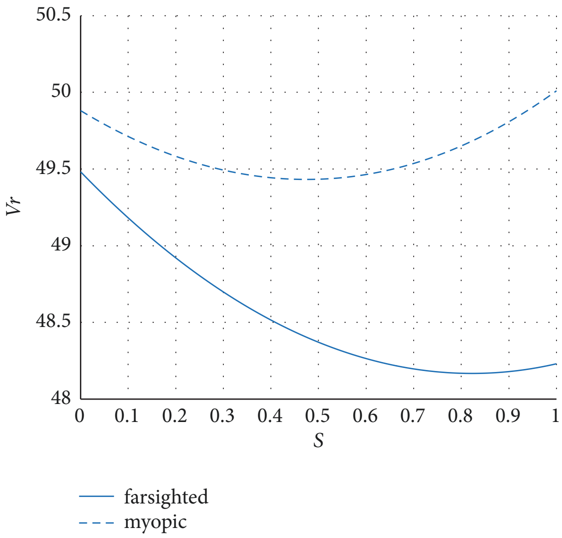

Figure 2: The profits of the retailer as S increases.

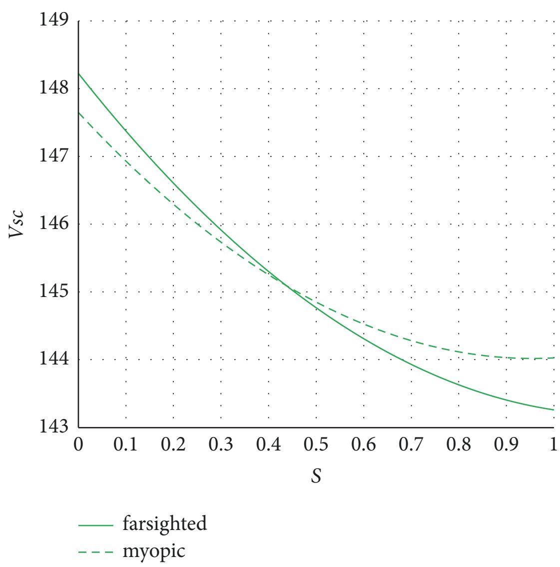

Figure 3: The profits of the whole supply chain as S increases.

prefers the decision on farsighted behavior, whereas the retailer prefers a myopic cooperator. Can this dilemma be solved? We should study the profits of the whole supply chain between two behaviors. From Figure 3, it is illustrated that when $S < 0.436$, the profits of the supply chain in the farsighted case are larger than those in the myopic case. Then, the best choice of the manufacturer is the farsighted behavior, which is consistent with the selection of the whole supply chain. Thus, the dilemma can not be solved.

However, when $S > 0.436$, the manufacturer's behavior choice is not consistent with the whole supply chain. In this situation, changing the choice of the manufacturer's behavior can deal with this dilemma [26]. It can resort to the lump sum transfer contract, which can handle this dilemma. Since $V_{sc}^M > V_{sc}^F$ when $S < 0.436$, where $V_{sc}^M = V_m^M + V_r^M$ and

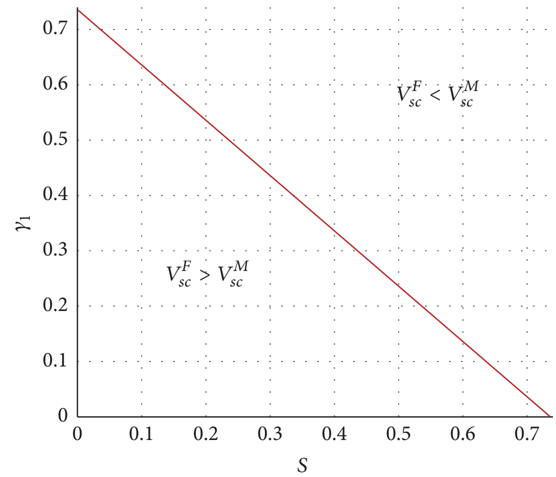

Figure 4: The comparison of the whole supply chain's profits in terms of γ_1 and S.

$V_{sc}^F = V_m^F + V_r^F$, the manufacturer opts to be myopia if it can gain a lump sum payment L_m $(V_m^F - V_m^M < L_m < V_r^M - V_r^F)$ as compensation from the retailer. Hence, the manufacturer changes to the myopic behavior, which is consistent with the retailer's preference.

Furthermore, in both the farsighted and the myopic scenarios, we find that the manufacturer's profits are decreasing in the emission permit price, while the retailer's profits are first decreasing and then increasing. This is because, on the one hand, the cost of the emission reduction is directly taken by the manufacturer and increases with the raising of the emission permit price. On the other hand, the retailer's profits are mainly influenced by the market demand, which depends on the retail price and the emissions. When the emission permit price is at a lower level, the market demand is mainly influenced by the retail price. In addition, the retailer raises the retail price since the manufacturer raises the wholesale price to make up for the emission cost. Thus, the demand is decreasing and the retailer's profits are correspondingly decreasing. On the contrary, when the emission permit price is at a higher level, the emissions play a major role in demand. A higher level of emission reduction leads to a higher demand. Therefore, the retailer gains more with the increase of the emission permit price.

In Figures 4 and 5, we compare the whole supply chain's profits with respect to S and γ_1, and S and γ_2, respectively. It is concluded that, for a certain emission permit price, the myopic manufacturer harvests a higher proportion of the whole supply chain's profits when the market demand is more sensitive to the emissions or when the reference emission effect is weaker. The reason is that the manufacturer's choice of myopic behavior results in a high level of emission reduction. From another point of view, for a fixed emission sensitivity or for a fixed marginal contribution of the gap between the emissions and the reference emissions on demand, the farsighted profits of the whole supply chain are higher when the emission permit price is relatively low. This is because a low emission permit price leads to a low level of

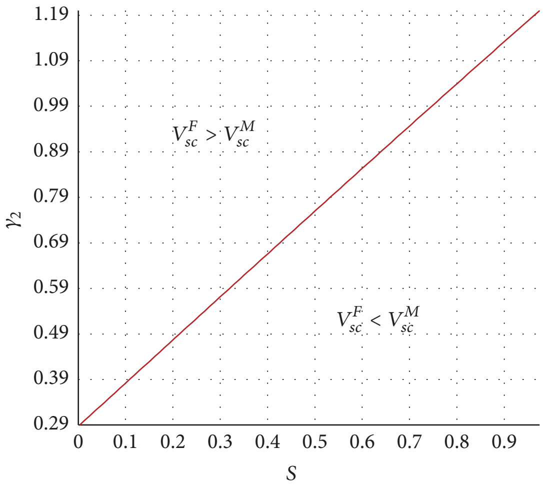

FIGURE 5: The comparison of the whole supply chain's profits in terms of γ_2 and S.

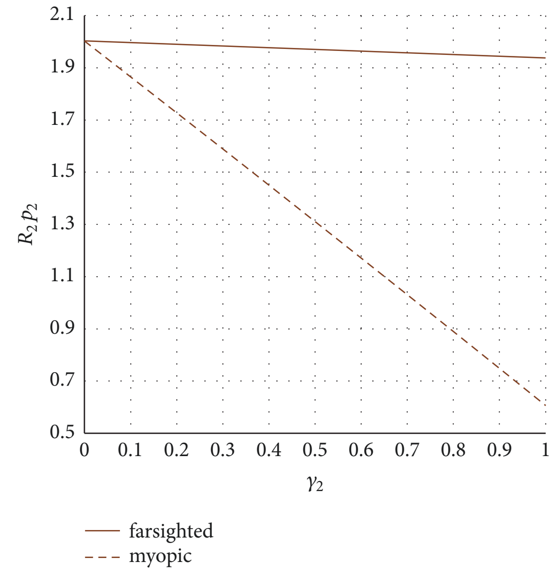

FIGURE 7: The emission-price product as γ_2 increases.

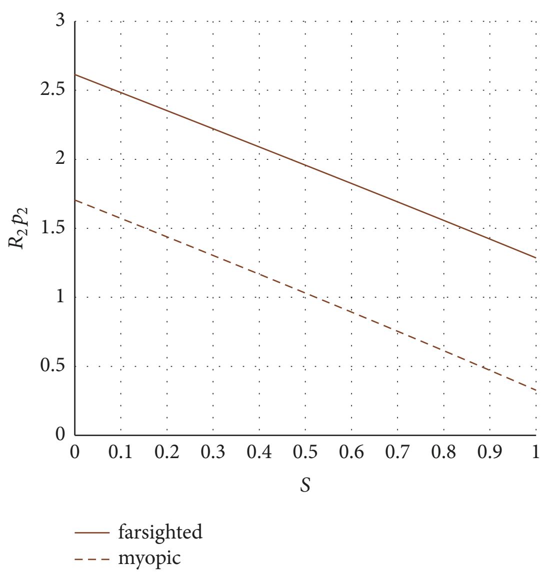

FIGURE 6: The emission-price product as S increases.

emission reduction and hence leads to high reference emissions. Therefore, the farsighted manufacturer considers the reference emissions and avoids the corresponding negative effects on customer demand. Thus, a farsighted manufacturer brings high profits to the whole supply chain.

In Figures 6 and 7, we investigate the effects of the parameters S and γ_2 on the interest of the consumers. As mentioned in Proposition 10, the welfare of the consumers can be measured by the emission-price product. The myopic behavior results in a better welfare to the consumers. From Figure 6, we find that the consumers' welfare increases as the emission permit price raises. Thus, for the government, setting a high emission permit price benefits not only the whole supply chain, but also the consumers. Figure 7 illustrates that, with the increase on the strength of the reference emission effects, the consumers' welfare gap between the two behaviors is enlarged. In other words, consumers can gain more when they are more sensitive to the difference between the actual emissions and the reference emissions.

6. Conclusions

Under dynamic situation, the supply chain members have two behavioral strategies to choose: to be farsighted or to be myopic. The former one considers the future influence of the current decision on the evolution of the state dynamics, while the latter one is only concentrated on the immediate profits. In order to investigate how the behavior choice affects the operations decisions and pay-offs of the supply chain members, we develop a Stackelberg differential game model, in which the manufacturer, as a leader, determines the wholesale price and the emission reduction level and the retailer, as a follower, makes a decision on the retail price. The effects of actual manufacturing emissions and reference emissions are also considered in this model. We give the comparison and analysis of emission reduction and pricing strategies as well as the profits in both the farsighted and the myopic scenarios. As a result, some interesting findings with managerial insights are obtained.

From the perspective of the supply chain members, we observe the following results. First, the farsighted manufacturer prefers to keep a lower level of emission reduction than the myopic one does. Second, the wholesale/retail price is higher (conversely, lower) in the farsighted scenario than that in the myopic scenario when the emission permit price is relatively higher (conversely, lower). However, the threshold of the emission permit price for the manufacturer is lower than that for the retailer. What is more, when the emission permit price is relatively high, the manufacturer's choice of farsighted behavior results in lower profits of the whole supply chain. Hence, this dilemma of the behavioral choice can be solved by the negotiation through a lump sum transfer contract. Then, the supply chain members can reach agreement and achieve Pareto improvement.

From the perspective of the consumers, we get a better understanding of the impacts of the behavior choice. A myopic manufacturer results in the high level of emission reduction and the low retail price when the emission permit price is relatively high (i.e., $S > 3\gamma_1/\beta$) and hence makes the consumers better off. By using the concept of emission-price product to measure the consumer welfare, we conclude that the condition for the better consumer welfare is much weaker than the former condition $S > 3\gamma_1/\beta$. In other words, a myopic manufacturer leads to a better consumer welfare in most cases. Moreover, it is beneficial for the consumers when they are more sensitive to the difference between the actual emissions and the reference emissions and/or the emission permit price is higher.

From the perspective of the government, we find that the emission quota affects only the manufacturer's profits and has no influence on retailer's profits and both the supply chain members' strategies. Thus, the government should allocate sufficient carbon quota to ensure profitability of the manufacturer firstly and then can raise the emission permit price in the carbon trade market indirectly by reducing the whole quota allocated to the industry. Therefore, the relatively high emission permit price leads the manufacturer to act as myopic behavior and results in the high level of both the emission reduction and the consumer welfare.

Although we obtain some important managerial insights in this paper, there exist some limitations which can be extended in future. First, the behavior choice of the retailer has no effect on the emission reduction and pricing strategies. Then, it can be considered that the retailer's pricing strategies influence the dynamics of the reference emissions, and hence the retailer's behavioral choice affects the decisions of both the supply chain members. Second, we only consider the dynamics of a single state, i.e., the reference emissions. Other factors, such as the reference price, the reference quality, the learning effect, and goodwill can be added into our models and studied simultaneously. Additionally, it may be interesting to make the supply chain structure more complicated, e.g., considering the competitions of two/multiple manufacturers or two/multiple retailers.

Appendix

A.

A.1. Proof of Proposition 1

Proof. The value functions V_r^F and V_m^F, which should be bounded and continuous, need to be established. This ensures that the solution $R(t)$ to (6a), (6b), and (6c) and the HJB Equations (9) and (10) is existent and unique.

Taking the first-order conditions with respect to w and τ for the right side of (10) yields

$$\alpha - 2\beta w + \beta c + \gamma_2 R + (\beta S - \gamma_1 - \gamma_2) E (1-\tau) = 0, \quad \text{(A.1)}$$

$$\begin{aligned} &SE(\alpha - \beta w + \gamma_2 R - E(\gamma_1 + \gamma_2)(1-\tau)) \\ &\quad + (w - c - SE(1-\tau))(\gamma_1 + \gamma_2) E - 2k\tau \\ &\quad - 2\theta E \frac{\partial V_m^F}{\partial R} = 0. \end{aligned} \quad \text{(A.2)}$$

Then, we get the wholesale price and the emission reduction level for the manufacturer as follows:

$$\begin{aligned} w = {} & \frac{\gamma_2 (2\beta k + (\gamma_1 + \gamma_2) E a_1 - a_1^2)}{\beta a_2} \cdot R \\ & + \frac{2\theta E (a_1 - 2(\gamma_1 + \gamma_2) E)}{a_2} \cdot \frac{\partial V_m^F}{\partial R} + \frac{\alpha + \beta c}{2\beta} \\ & + \frac{(a_1 - 2(\gamma_1 + \gamma_2) E)(4\beta k - (\alpha - \beta c) a_1)}{2\beta a_2}, \end{aligned} \quad \text{(A.3)}$$

$$\tau = \frac{\gamma_2 a_1}{a_2} \cdot R - \frac{4\beta\theta E}{a_2} \cdot \frac{\partial V_m^F}{\partial R} + \frac{a_1 a_3}{a_2}. \quad \text{(A.4)}$$

Substituting (A.3) and (A.4) into (8) produces

$$\begin{aligned} p = {} & \frac{\gamma_2 (3\beta k + (\gamma_1 + \gamma_2) E a_1 - a_1^2)}{\beta a_2} \cdot R \\ & + \frac{\theta E (a_1 - 4(\gamma_1 + \gamma_2) E)}{a_2} \cdot \frac{\partial V_m^F}{\partial R} + \frac{3\alpha + \beta c}{4\beta} \\ & + \frac{(a_1 - 4(\gamma_1 + \gamma_2) E)(4\beta k - (\alpha - \beta c) a_1)}{4\beta a_2}. \end{aligned} \quad \text{(A.5)}$$

Then, inserting (A.3)-(A.5) into (10) yields

$$\begin{aligned} \rho V_m = {} & \frac{k\gamma_2^2}{2a_2} \cdot R^2 - \frac{\theta a_4}{a_2} \cdot R \frac{\partial V_m}{\partial R} + \frac{2\beta\theta^2 E^2}{a_2} \cdot \left(\frac{\partial V_m}{\partial R}\right)^2 \\ & + \frac{k\gamma_2 a_3}{a_2} \cdot R + \frac{\theta E (a_2 - a_1 a_3)}{a_2} \cdot \frac{\partial V_m}{\partial R} + \frac{k a_3^2}{2a_2} \\ & + SE_0. \end{aligned} \quad \text{(A.6)}$$

Conjecture the following quadratic value function of the manufacturer

$$V_m = x_2 R^2 + x_1 R + x_0, \quad \text{(A.7)}$$

where x_0, x_1, and x_2 are constants, which should be determined in the following. Substituting (A.7) and the partial derivatives of the value function into (A.6) and equating corresponding coefficients yield

$$\rho x_2 = \frac{k\gamma_2^2}{2a_2} - \frac{2\theta a_4}{a_2} x_2 + \frac{8\beta\theta^2 E^2}{a_2} x_2^2, \quad \text{(A.8)}$$

$$\begin{aligned}\rho x_1 = &-\frac{\theta a_4}{a_2}x_1 + \frac{8\beta\theta^2E^2}{a_2}x_1x_2 + \frac{2\theta E(a_2 - a_1a_3)}{a_2}x_2 \\ &+ \frac{k\gamma_2 a_3}{a_2},\end{aligned} \tag{A.9}$$

$$\rho x_0 = \frac{2\beta\theta^2E^2}{a_2}x_1^2 + \frac{\theta E(a_2 - a_1a_3)}{a_2}x_1 + \frac{ka_3^2}{2a_2} + SE_0. \tag{A.10}$$

Thus, it follows from (A.8) that

$$x_2 = \frac{\rho a_2 + 2\theta a_4 \pm \Delta}{16\beta\theta^2E^2}. \tag{A.11}$$

If we select the larger root of (A.11), the dynamics of reference emission would not converge to a steady-state value in the further calculation. Hence, in the following discussions, we only consider the smaller root, i.e.,

$$x_2 = \frac{\rho a_2 + 2\theta a_4 - \Delta}{16\beta\theta^2E^2}. \tag{A.12}$$

Substituting (A.12) into (9) and (10) yields

$$x_1 = \frac{a_5(a_2 - a_1a_3) + 8\beta\theta Ek\gamma_2a_3}{4\beta\theta E(\Delta + \rho a_2)}, \tag{A.13}$$

$$\begin{aligned}x_0 = &\frac{SE_0}{\rho} + \frac{ka_3^2}{2\rho a_2} \\ &+ \frac{(a_2 - a_1a_3)(a_5(a_2 - a_1a_3) + 8\beta\theta Ek\gamma_2a_3)}{4\rho\beta a_2(\Delta + \rho a_2)} \\ &+ \frac{(a_5(a_2 - a_1a_3) + 8\beta\theta Ek\gamma_2a_3)^2}{8\rho\beta a_2(\Delta + \rho a_2)^2}.\end{aligned} \tag{A.14}$$

Then, substituting the partial derivatives of the value function into (A.3)-(A.5), we can get the wholesale price, emission reduction level, and the retail price, i.e., (18)-(20). Substituting the above results into (9) and following the same computational procedure as the value function of the manufacturer, we get the value function of the retailer which is shown in (22). □

A.2. Proof of Proposition 2

Proof. Substituting the equilibrium emission reduction level, i.e., (18), into the state equation, i.e., (1), we have the following differential equation:

$$\dot{R}(t) = \frac{\rho a_2 - \Delta}{2a_2}R + \frac{2\theta Ea_6}{a_2(\Delta + \rho a_2)}. \tag{A.15}$$

A particular solution to (A.15) is given by

$$R_\infty = \frac{4\theta Ea_6}{\Delta^2 - \rho^2a_2^2}. \tag{A.16}$$

Then, according to the initial condition $R(0) = R_0$, we obtain the corresponding solution shown in (26). Moreover, substituting (26) into (18)-(20) yields the corresponding control paths shown in (23)-(25). Substituting (23)-(25) into (2), we have the demand path shown in (27). □

A.3. Proof of Corollary 3. In virtue of (23)-(25) in Proposition 2, the corresponding strategies can be obtained immediately.

A.4. Proof of Corollary 4

Proof. From (29), we get

$$\frac{\partial R_\infty^F}{\partial \rho} = -\frac{64\beta\theta^3E^2k\gamma_2a_2^2(\gamma_2E + a_3)}{(\Delta^2 - \rho^2a_2^2)^2} < 0, \tag{A.17}$$

$$\frac{\partial R_\infty^F}{\partial \gamma_2} = -\frac{4\beta kE^2\rho(\rho + \theta)(\alpha - \beta c - \beta SE - \gamma_1E)}{A_0^2} < 0, \tag{A.18}$$

$$\frac{\partial R_\infty^F}{\partial \theta} = \frac{4\beta kE^2\rho\gamma_2(\alpha - \beta c - \beta SE - \gamma_1E)}{A_0^2} > 0, \tag{A.19}$$

$$\frac{\partial R_\infty^F}{\partial k} = \frac{4\beta E^2(\rho + \theta)(\rho(\beta S + \gamma_1 + \gamma_2) + \theta(\beta S + \gamma_1))(\alpha - \beta c - \beta SE - \gamma_1E)}{A_0^2} > 0, \tag{A.20}$$

since the demand should be positive, i.e., $\alpha - \beta c - \beta SE - \gamma_1E > 0$, where

$$\begin{aligned}A_0 = &(\rho + \theta)(\gamma_1 + \beta S)^2E^2 + \rho\gamma_2(\gamma_1 + \beta S)E^2 \\ &- 4\beta k(\rho + \theta).\end{aligned} \tag{A.21}$$

Then, we get the second column in Table 1. From (29)-(33), it is clear that

$$\tau_\infty^F = 1 - \frac{R_\infty^F}{E}, \tag{A.22}$$

$$w_\infty^F = \frac{\alpha + \beta c}{2\beta} + \frac{(\beta S - \gamma_1)R_\infty^F}{2\beta}, \tag{A.23}$$

$$p_\infty^F = \frac{3\alpha + \beta c}{4\beta} + \frac{(\beta S - 3\gamma_1)R_\infty^F}{4\beta}, \tag{A.24}$$

$$D_{\infty}^{F} = \frac{\alpha - \beta c}{4} - \frac{(\beta S + \gamma_1) R_{\infty}^{F}}{4}. \quad (A.25)$$

Thus, taking the first-order partial derivative of w_{∞}^{F}, p_{∞}^{F}, D_{∞}^{F} with respect to parameters ρ, γ_2, θ and k, respectively, we can easily get the rest of the columns in Table 1. □

A.5. Proof of Proposition 5. The proof of Proposition 5 is similar to those of Propositions 1 and 2.

A.6. Proof of Corollary 6

Proof. On the basis of (40) and (41), we have $V_{m,m}^{M}(R) - V_{r}^{M}(R) = ((2\beta k - ((\beta S + \gamma_1 + \gamma_2)E)^2)/2\beta k)V_{r}^{M}(R)$. Thus, it is known that $V_{m,m}^{M}(R) < V_{r}^{M}(R)$ if $S > \sqrt{2k}/E\sqrt{\beta} - (\gamma_1 + \gamma_2)/\beta$; $V_{m,m}^{M}(R) = V_{r}^{M}(R)$ if $S = \sqrt{2k}/E\sqrt{\beta} - (\gamma_1 + \gamma_2)/\beta$; and $V_{m,m}^{M}(R) > V_{r}^{M}(R)$ if $S < \sqrt{2k}/E\sqrt{\beta} - (\gamma_1 + \gamma_2)/\beta$. □

A.7. Proof of Corollary 7. By virtue of (35)-(37) in Proposition 5, we can easily get the corresponding strategies in the myopic scenario.

A.8. Proof of Corollary 8. The proof of Corollary 8 is similar to that of Corollary 4.

A.9. Proof of Proposition 9

Proof. Table 1 shows that τ_{∞}^{F} is increasing in ρ; w_{∞}^{F} is decreasing in ρ if $S > \gamma_1/\beta$ holds and increasing in ρ otherwise; p_{∞}^{F} is decreasing in ρ if $S > 3\gamma_1/\beta$ holds and increasing in ρ otherwise. Moreover, when $\rho \longrightarrow +\infty$, all the steady-state strategies in the farsighted scenario are in accord with those in the myopic scenario. Thus, Proposition 9 is obtained immediately. □

A.10. Proof of Proposition 10

Proof. Let $G(R_{\infty}^{F}) = R_{\infty}^{F} p_{\infty}^{F}$. From (A.24), we have $G(R_{\infty}^{F}) = R_{\infty}^{F}((3\alpha + \beta c)/4\beta + ((\beta S - 3\gamma_1)/4\beta)R_{\infty}^{F})$, and then $dG(R_{\infty}^{F})/dR_{\infty}^{F} = ((\beta S - 3\gamma_1)/2\beta)R_{\infty}^{F} + (3\alpha + \beta c)/4\beta$. Since $R_{\infty}^{F} \longrightarrow R_{\infty}^{M}$ when $\rho \longrightarrow +\infty$, and $\partial R_{\infty}^{F}/\partial\rho < 0$ derived from the proof of Corollary 3, as a result, we get Proposition 10. □

Abbreviations

OECD: Organization for Economic Cooperation and Development
HJB: Hamiltonian-Jacobi-Bellman.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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