A Study on Pricing and Emission Reduction Decision of Steel Supply Chain under Free Carbon Quota Policy

Yanling Wu^a, Zhigao Liao^b and Yu Chen^c

School of Management, Guangxi University of Science & Technology, Liuzhou 545006, China.

^awyl521510@163.com, ^b46154910@qq.com, ^ccy31600@163.com

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Abstract. Considering that the retailer bears part of the manufacturer's emission reduction cost, this paper analyzes the optimal pricing and optimal emission reduction decisions for the two-level steel supply chain under the carbon-free policy, historical method and benchmark method. The numerical example shows that the emission reduction cost sharing rate is positively related to the manufacturer's emission reduction rate. Compared with the historical method, the benchmark method can effectively promote the manufacturers to reduce carbon emission. Under the benchmark method, when the retailer bears the appropriate emission reduction cost for manufacturers, it can promote the two-way development of the steel supply chain economy and emission reduction.

1. Introduction

The emission of greenhouse gases leads to global warming, which has become an important issue for the sustainable development of the global economy. As a pillar industry of China's national economy, the steel industry accounts for about 15% of the country's total carbon emissions. The steel industry is one of the emission reduction industries, and China has not proposed a clear carbon quota allocation method. At present, the national carbon trading market is in the prototype stage. Most carbon trading pilots use free distribution, and there are mainly historical method and benchmark method for free distribution. Therefore, adopting the historical method or the benchmark method has become a practical issue in the steel industry. In addition, the issue of supply chain operation decision-making under the carbon trading policy has also gradually received the attention of some scholars. In terms of pricing and production decision-making, Xu et al discussed the issue of joint production and pricing of manufacturers under cap-and-trade and carbon tax policies[1]; Jialing Jiao constructed two kinds of game models about the enterprise to join the carbon trading system and accept the extra punishment without joining, and the effects of different emission quotas, transaction prices, and penalties on the pricing decisions of the enterprise were explored through numerical simulation [2]. In terms of inventory management and order quantity, Song et al used the newsboy model to analyze the issue of single-cycle optimal order quantity decision-making under the three kinds of carbon emission policies under random demand [3]; In the two-stage supply chain system composed of suppliers and purchasers, Wei Zeng solved the optimal order quantity of enterprises under the carbon trading mechanism through economic batch model [4]. In addition to the above researches, some scholars have also conducted research on emission reduction decisions. Yourdon Li and Daisha Zhao constructed two game forms, Nash game and Stackelberg game, which were made up of manufacturers and retailers, and obtained government subsidies and strategy for cooperative emission reduction of supply chain companies under the different forms of game [5].

To sum up, the research on the impact of carbon trading on supply chain operations has mainly focused on the aspects of pricing, production, inventory management, and optimal order quantity, etc. There is relatively little research on carbon emission reduction. In the few literatures on carbon emission reduction, few literatures have conducted in-depth research on carbon trading policies. Based on this, this article analyzes the pricing and emission reduction decisions of the steel supply

chain under different free carbon quota policies, taking into account the retailer's sharing of the manufacturer's emission reduction costs.

2. Problem Description and Model Hypothesis

At present, there are many uncontrolled companies that are not subject to carbon trading policies in the steel supply chain, which is not conducive to the overall emission reduction of the steel supply chain. In view of this, this paper constructs a two-level supply chain consisting of a steel manufacturer and a steel retailer. The steel manufacturer is the control company, the steel retailer is the non-control company, and the country considers the supply chain as a whole and supply chain carbon quota to the manufacturer. The manufacturer carries out carbon emission reductions under the constraints of carbon trading policies. At the same time, it constrains the retailer through product pricing, and the retailer bears some carbon emission reduction costs of the manufacturer. After both sides of the game to achieve the goal of common emission reduction.

This article has the following hypothesis.

Hypothesis 1: According to the assumption of the classical model standard, the manufacturer's carbon emission reduction cost has a secondary relationship with its emission reduction rate, $C(\tau_i) = 1/2\beta_i(\tau_i)^2$, β_i is emission reduction investment cost factor, and $\beta_i > 0, 0 < \tau_i < 1$ [6].

Hypothesis 2: As consumers' low-carbon awareness increases, consumer demand meets $Q = a - bp_r + c\tau_m$, a is the original market demand of the product, b is the impact factor of price on market demand, and c is the sensitivity of consumers to carbon emissions. And $a > 0, b > 0, a > bp_r, c > 0$ [7].

The main model parameters of this article are as follows: p_m and p_r refer to the unit wholesale price and retail price; c_m and c_r refer to the total cost per unit of manufacturer, retailer; τ_m refers to the emission reduction rate; Q refers to the demand; e_m refers to the carbon emissions from unit products before reduction; ξ_m refers to the carbon quotas allocated according to total amount; α_m refers to the carbon quotas allocated per unit of production; p_e refers to the unit carbon trading price; λ refers to the emission reduction cost sharing rate; π_m, π_r and π refer to the profits of the manufacturer, the retailers and supply chain.

3. The Establishment and Solution of the Model

3.1 Carbon-Free Policy Game Model.

Without the carbon policy, the manufacturer's profits consist of sales revenue and carbon emission reduction costs, the retailer's profits consist of sales revenue and share of the manufacturer's carbon emission reduction costs. The manufacturer prioritizes the decision on the wholesale price and the emission reduction rate, then the retailer determines the retail price. The game model is as follows:

$$\pi_{m1} = (p_m - c_m)Q - \frac{1}{2}(1 - \lambda)\beta_m\tau_m^2 \quad (1)$$

$$\pi_{r1} = (p_r - p_m - c_r)Q - \frac{1}{2}\lambda\beta_m\tau_m^2 \quad (2)$$

3.2 Game Model Based on History Method.

The historical method refers to the method of determining the carbon emission quota for future years by using the carbon emissions data of units that have been included in the quota management in the previous year as the main basis. Under this policy, the game model is as follows:

$$\pi_{m2} = (p_m - c_m)Q - [e_m(1 - \tau_m)Q - \xi_m]p_e - \frac{1}{2}(1 - \lambda)\beta_m\tau_m^2 \quad (3)$$

$$\pi_{r2} = (p_r - p_m - c_r)Q - \frac{1}{2}\lambda\beta_m\tau_m^2 \quad (4)$$

3.3 Game Model Based on the Benchmark Method.

The benchmark method is to set a benchmark first, and then determine the allocation of quota based on the product of the actual emissions of the regulated companies and the benchmark. This game model is as follows:

$$\pi_{m3} = (p_m - c_m)Q - [e_m(1 - \tau_m) - \alpha_m]Qp_e - \frac{1}{2}(1 - \lambda)\beta_m\tau_m^2 \quad (5)$$

$$\pi_{r3} = (p_r - p_m - c_r)Q - \frac{1}{2}\lambda\beta_m\tau_m^2 \quad (6)$$

3.4 Game Result Analysis.

Proposition 1: Under historical method, let $A = a - b(c_m + c_r)$, $B = c + be_m p_e$, if $4b\beta_m(1 - \lambda) - B^2 > 0$, there was a unique optimal solution for corporate decisions in the supply chain:

$$\begin{cases} p_{m2} = \frac{2\beta_m(1 - \lambda)[a + b(c_m - c_r + e_m p_e)] - B[c \cdot c_m + (a + c - bc_r)e_m p_e]}{4b\beta_m(1 - \lambda) - B^2} \\ \tau_{m2} = \frac{B(A - be_m p_e)}{4b\beta_m(1 - \lambda) - B^2} \\ p_{r2} = \frac{(1 - \lambda)\beta_m[3a + b(c_m + c_r + e_m p_e)] - B[c(c_m + c_r) + (a + c)e_m p_e]}{4b\beta_m(1 - \lambda) - B^2} \end{cases}$$

Proof: Using the inverse induction method to solve, formula (4) finds the first derivative of p_r , makes it equal to zero, brings the value of the solution into Q , then Q into formula (3), and it takes the partial derivative with respect to p_m add τ_m . Let it be equal to zero. When $4b\beta_m(1 - \lambda) - B^2 > 0$, we get: p_{m2} and τ_{m2} . At this time, the Hessian matrix of formula (3) is negative definite, so p_{m2} and τ_{m2} are the optimal solutions of formula (3). Substituting p_{m2} and τ_{m2} into p_r gives p_{r2} . This p_{r2} is the optimal solution of (4), and Proposition 1 is proved.

Proposition 2: There are the following relationships between the emission reduction rates under the two carbon policies: $\tau_{m2} < \tau_{m3}$

Proof: $\tau_{m3} - \tau_{m2} = \frac{b\alpha_m p_e (c + be_m p_e)}{4b(1 - \lambda)\beta_m - (c + be_m p_e)^2} > 0$, it can be seen that the emission reduction rate under

the benchmark method is always greater than the emission reduction rate under the historical method, which means that the benchmark method can promote the emission reduction of manufacturers more than the historical method.

4. The Example Analysis

In order to analyze the influence of the emission reduction cost sharing rate on the supply chain decision variables in the above three models, this section uses a numerical analysis method to perform the correlation analysis. Under the condition of satisfying the optimal solution, let $a = 100$, $b = 1.25$, $\beta_m = 200$, $p_e = 1$, $c_m = 15$, $c_r = 3$, $e_m = 3$, $\xi_m = 60$, $\alpha_m = 2$, $c = 2$. Figure 1 to figure 6 respectively represent the impact of emission reduction rate on emission reduction rate, wholesale price, retail price, manufacturer profit, retailer profit and total supply chain profit.

Fig. 1. Effect of λ on τ_m

Fig. 2. Effect of λ on p_r

Fig. 3. Effect of λ on p_m

Fig. 4. Effect of λ on π_m

Fig. 5. Effect of λ on π_r

Fig. 6. Effect of λ on π

Through numerical analysis, it is found that data with λ greater than 0.7 is subject to greater fluctuations. Considering the fact that retailers cannot afford more than 70% of λ , the range of λ for this study is between 0 and 0.7. From Figure 1 to Figure 6, it can be seen that in addition to Figure 2 and Figure 5, the decision variable images under the non-policy are basically under two kinds of carbon policies, which shows that the implementation of carbon policies is beneficial to supply companies.

Figure 1 shows that $\tau_{m1} < \tau_{m2} < \tau_{m3}$, verifying Proposition 2. In addition, τ_m increases with the increase of λ , which means that the retailer's sharing of emission reduction costs for manufacturers can promote carbon emission reduction by manufacturers. In Figure 2 and Figure 3, p_r under the carbon policy decreases with the increase of λ , while p_m increases with the increase of λ , which means that the greater the emission reduction cost the retailer bears, the greater the total cost of the retailer, the smaller the total cost of the manufacturer. Figure 4 and figure 5 shows that π_m increase with the increase of λ , and π_r are reduced with the increase of λ , indicating that the increase of λ enables manufacturers to reduce costs and improve profits, but it increases the retailer's cost and reduces the profit. Figure 6 shows that the graph under the carbon policy first rises and then falls, indicating that λ is not the bigger the better. When $\lambda = 0.3$, the total profits of the supply chain under the carbon policy have reached the maximum value and are much greater than the total profits without policies.

5. Conclusion

This paper constructs a two-level Steinberg game model to study the optimal decision-making of supply chain members under the carbon-free policy, historical method and benchmark method. The study found that with the historical method, the benchmark method is more effective in promoting carbon reduction by steel manufacturers. The benchmark method is more suitable for the development of the steel supply chain, because under the benchmark law, when $\lambda = 0.3$, emission

reductions are maximized, and profits of manufacturers and retailers are greater than those of carbon-free policies. Under the historical law, the profit of the manufacturer is greater than that of the carbon-free policy, while the retailer's profit is less than the profit when the carbon-free policy is adopted. Therefore, for the steel supply chain, under the benchmark method, when the retailer bears the appropriate emission reduction cost for the manufacturer, it can not only promote low-carbon emission reduction in the steel supply chain, but also promote the economic development of the steel supply chain.

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