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Research Article

A Study on the Pricing Decision of Remanufacturing Products considering Government Subsidies in a Carbon Trading Environment

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Considering the characteristics of the carbon trading environment, the impact of government subsidies on pricing decisions of remanufacturing products is studied. First of all, four cases, including those without government subsidies, government subsidies for manufacturers', government subsidies for retailers', and centralized decision-making, are analyzed, respectively, and the optimal solutions of new products and remanufacturing products are obtained in four cases. Then, three cases of production subsidies, sales subsidies, and centralized decision-making are compared and analyzed, and the influences of government subsidies on wholesale prices, sales prices, and sales volume are revealed. Finally, the influences of main factors on decision variables and optimal profits are analyzed through numerical simulation, and the main conclusions are verified. The study finds that (1) under two subsidy mechanisms of production subsidies and sales subsidies, the government has the same promoting effect on the sales volume of remanufacturing products; (2) compared with government subsidies to manufacturers or retailers, in the way that manufacturers and retailers make centralized decisions on government subsidies, the sales volume of products increases, and the profits of the entire remanufacturing product supply chain system are optimized.

1. Introduction

In recent years, the two major problems of serious resource shortage and environmental pollution have plagued China, which has attracted the common concern of both academic and business circles. On the one hand, the recycling of resources makes the remanufacturing industry based on the closed-loop supply chain has become an important way to realize the sustainable development strategy in China. On the other hand, manufacturing enterprises urgently need to take active measures to reduce CO_2 emissions to solve the local environmental pollution problem. Of course, facing the pressure of CO_2 emission reduction, it is also necessary for the government to launch corresponding energy-saving and emission reduction policies to coordinate the contradiction between high-quality economic development and environmental pollution. The carbon trading mechanism means that the government sets a CO_2 emission cap for enterprises according to the characteristics of different industries, and the enterprises sell excess carbon credits and buy shortage carbon credits in the carbon trading market according to their own CO_2 emission situation. The supply chain of remanufacturing products is actually a reverse supply chain, including recycling, sorting, testing, dismantling, remanufacturing, and sales. Therefore, the price of remanufacturing products will be influenced by both the strategies of recyclers and those of manufacturers and retailers. In practice, Huawei, Apple, Xiaomi, and other companies refurbish recycled used electronics to eventually form remanufacturing products. On the one hand, although the level of remanufacturing products can be analogous to or even exceed that of new products, the lack of full understanding of remanufacturing products by consumers leads to a relatively low expected value and willingness to purchase remanufacturing products, and companies will have a difficult pricing problem. On the other hand, due to the lack of

consumers' willingness to actively participate in recycling used products, enterprises usually do not invest too much in the recycling business of used products, resulting in an unstable market environment for the recycling of used products, making it difficult to form the scale effect of remanufacturing industry, and enterprises cannot obtain larger profits from remanufacturing business. Therefore, under the carbon trading mechanism, it is of great practical significance to thoroughly study the pricing of remanufacturing products, which is conducive to solving the dilemma of pricing remanufacturing products.

2. Literature Review

Much of the literature studies the pricing decision of remanufacturing products with considering government subsidies and the carbon trading environment. Here, we mainly review the relevant literature primarily related to three streams of research: first, the pricing decision of remanufacturing products/supply chain; second, the pricing of remanufacturing products/supply chains in the carbon trading environment; the last stream of research reviews the impact of government subsidy on remanufacturing products/supply chain pricing decisions.

2.1. The Pricing Decision of Remanufacturing Products. In recent years, scholars have done a lot of research on the pricing decision of the remanufacturing product/supply chain. Xu et al. [1] study the impact of technological innovation on the pricing of the remanufacturing product based on the Stackelberg game model, considering two-game subjects of the original manufacturer and the third-party remanufacturer. Yenipazarli [2] discusses the impact of carbon tax policy on the optimal pricing and production decisions of remanufacturing enterprises. Li et al. [3] explore the effect of quality level on the optimal recycling pricing and production decision of the remanufacturing product. Qiao and Su [4] investigate the optimal pricing and quality of the remanufacturing product under two major markets by distinguishing between nonsegmented and segmented markets. Zheng et al. [5] investigate the optimal production and pricing decision of the remanufacturing product under a two-stage model by considering customers' bias and accurate response.

2.2. Carbon Cap-and-Trade Policy. With the full implementation of the carbon cap-and-trade policy in China, more and more scholars focus on the impact of the carbon trading mechanism on the pricing decision of the remanufacturing product/supply chain. Chang et al. [6] construct a two-stage production and pricing decision model for manufacturers with and without a competitive substitution relationship approach between new and remanufacturing products and find that the carbon trading mechanism has a very important role in remanufacturing activities. Gan et al. [7] study the optimal retail and wholesale prices of the remanufacturing product under the carbon trading mechanism by considering different consumers' willingness to pay for the products. Wang et al. [8] construct a manufacturer production and pricing decision model with and without the financial constraint approach based on the carbon trading mechanism perspective. Miao et al. [9] introduce the carbon trading policy and construct a "trade-ins" subsidized manufacturer pricing and production decision model, and the study finds that the carbon trading policy is beneficial to increase the sales volume of the remanufacturing product.

2.3. Government Subsidy. As an effective way to enhance environmental protection benefits and motivate manufacturing enterprises to green production, government subsidies are crucial in remanufacturing supply chain operations. Therefore, the influence of government subsidies on the pricing decision of the remanufacturing product/supply chain has also attracted more and more attention from scholars. Lou et al. [10] discuss the pricing decision of a three-level supply chain consisting of new product retailers, remanufacturing product retailers, and manufacturers under limited government subsidies. Chen et al. [11] construct a remanufacturing supply chain pricing and recycling decision model without/without government subsidies under the carbon trading mechanism, and the study shows that government subsidies play a very important role in recycling remanufacturing and carbon reduction activities compared to the no-subsidy approach. Meng et al. [12] investigate the impact of optimal consumption subsidy policy on the optimal pricing strategy of a closed-loop supply chain by considering the government, new product manufacturers, and remanufacturing product manufacturers as the three main game players. Wang et al. [13] explore the impact of subsidy policy on the production and pricing decisions of remanufacturing products based on a two-cycle dynamic model. Wan and Hong [14] explore the optimal pricing decision model of the closed-loop supply chain under dual recycling channels based on the government subsidy perspective. Du and Jing [15] explore the impact of government "trade-ins" subsidies on the pricing and production decisions of remanufacturing products by constructing a two-stage differential pricing model.

In summary, the existing literature mainly studies the pricing decision of the remanufacturing product/supply chain from the perspective of carbon trading mechanism or government subsidies, but less literature considers the impact of the investment of carbon emission reduction on the pricing decision of remanufacturing products. This paper considers the characteristics of the carbon trading environment, explores the influence of government subsidies on the pricing decision of remanufacturing products, analyzes the influence of related factors on the optimal decision through numerical simulation, and finally puts forward some countermeasure suggestions for the relevant subjects to make better pricing decision of remanufacturing products and promote the development of green low-carbon circular economy.

Compared with the existing studies, the innovations of this paper are: (1) introducing the carbon trading mechanism into the Stackelberg model, considering the market

competition of new products and remanufacturing products, taking government subsidies and the cost of carbon emission reduction as the main influencing factors, the remanufacturing product pricing decision model in four ways, including without government subsidies, government subsidies for manufacturers to produce remanufacturing products, government subsidies for retailers to sell remanufacturing products, and government subsidies in centralized decision-making, are constructed. (2) The optimal decision variables such as the wholesale price, retail price, sales volume, and supply chain profit of remanufacturing products under the four methods are compared and analyzed, which has some reference value for how the government selects the subsidy method and sets the subsidy amount.

3. Problem Description and Basic Assumptions

The pricing system for the remanufacturing products presented in this article is shown in Figures 1 and 2. Figure 1 shows the pricing decision model of remanufacturing products in the carbon trading environment without government subsidies, and Figure 2 shows the pricing decision model of remanufacturing products considering government subsidies in the carbon trading environment.

This paper discusses the impact of government subsidies and costs of carbon emission reduction on the pricing decisions of remanufacturing products in a carbon trading environment. To model and analyze the issues discussed, the necessary assumptions are given as follows:

Hypothesis 1. The manufacturer, as the leader of the remanufacturing supply chain, is responsible for the production of new and remanufacturing products. The production cost per unit of new and remanufacturing products is c_n and c_r, respectively. The manufacturer sells them to the retailer at the unit wholesale price of w_n and w_r. The retailer, as the follower of the remanufacturing supply chain, sells new and remanufacturing products to consumers at a unit retail price of p_n and p_r. The manufacturer directly recovers the waste products that meet the remanufacturing quality requirements, and the unit recovery cost is c_u.

Hypothesis 2. In the face of increasing emission reduction and competitive pressure, the manufacturer has to reduce emissions. However, the carbon emissions amount of the manufacturer producing per unit of new and remanufacturing products is e_n and e_r, respectively. Under the carbon trading mechanism, the government gives the manufacturer a certain free carbon emission quota, and the quota per unit of new and remanufacturing products is $(1-\mu)e_n$ and $(1-\mu)e_r$, respectively, indicating that the emission reduction target coefficient is set by the government according to the historical carbon emission intensity of the manufacturer. The larger $\mu\,(0 \le \mu \le 1)$ is, the fewer the carbon emission quota is and the greater the pressure to reduce emissions the manufacturer receives. Therefore, under the carbon trading mechanism, the manufacturer will meet the emission reduction targets set by the government through emission reduction investment. At the same time, the carbon emission rights of per unit of new and remanufacturing products are μe_n and μe_r, respectively and are sold to enterprises in the trading market, and the trading price of unit carbon emission rights is p_c. The investment coefficient of unit carbon emission reduction for new and remanufacturing products is γ_n and γ_r, respectively. According to the research of Debabrata and Shah [16], the unit emission reduction cost of the manufacturer for producing a new product is $\gamma_n \mu^2 e_n^2/2$, and the unit emission reduction cost of producing a remanufacturing product is $\gamma_r \mu^2 e_r^2/2$.

Hypothesis 3. Assuming that the initial total capacity of the product is Q. There are two products in the market, and the willingness of consumers to pay for remanufacturing products and new products is λ and $\varepsilon\lambda$, respectively, and the random variables obey the uniform distribution, which is the price sensitivity coefficient. The utility function for consumers to buy new products and remanufacturing products is $U_n = \lambda - p_n$ and $U_r = \varepsilon\lambda - p_r$, respectively. Therefore, according to the research of Zhang et al. [17], the demand function of the new product and the remanufacturing product is set as $D_n = Q - p_n - p_r/1-\varepsilon$ and $D_r = \varepsilon p_n - p_r/1-\varepsilon$, respectively. At this point, the total carbon emission amount of the manufacturer is $E = e_n D_n + e_r D_r$.

Hypothesis 4. This paper considers the problems under different methods, such as government subsidies for the manufacturer, government subsidies for the retailer, and government subsidies during centralized decision-making. k_m, k_r and k are different subsidies parameters under different methods.

Hypothesis 5. The pricing decision order of remanufacturing products is as follows. First, the manufacturer determines the wholesale price of w_n and w_r, then the retail price of p_n and p_r is determined by the retailer. π_i^j represents profits of supply chain members and system. $i = M, R, S$ denotes the profit of the manufacturer, retailer, and supply chain system, respectively; $j = a, b, c, d$ denotes the without government subsidies, the government subsidies for the manufacturer to produce remanufacturing products, the government subsidies for the retailer to sell remanufacturing products, and the government subsidies when the decision is centralized, respectively.

4. Without Government Subsidies

In this way, the government does not subsidize, and the demand functions of new and remanufacturing products are set as follows:

$$D_n = Q - \frac{p_n - p_r}{1-\varepsilon}, \qquad D_r = \frac{\varepsilon p_n - p_r}{1-\varepsilon}. \tag{1}$$

The profit function of the manufacturer is set as follows:

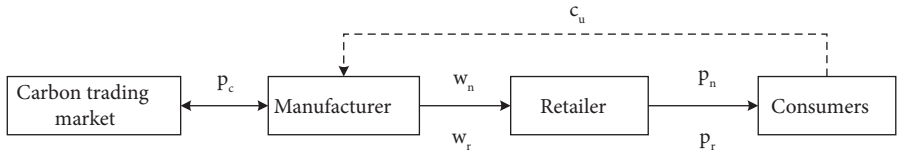

Figure 1: Operation process of the pricing system for remanufacturing products in the carbon trading environment.

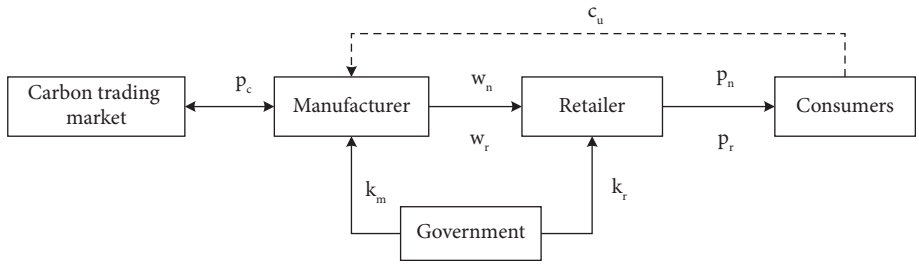

Figure 2: Operation process of the pricing system for remanufacturing products considering government subsidies in the carbon trading environment.

$$\pi_M^a = \left(w_n - c_n - \frac{\gamma_n \mu^2 e_n^2}{2} + p_c u e_n\right) D_n + \left(w_r - c_r - c_u - \frac{\gamma_r \mu^2 e_r^2}{2} + p_c u e_r\right) D_r. \tag{2}$$

The profit function of the retailer is set as follows:

$$\pi_R^a = (p_n - w_n) D_n + (p_r - w_r) D_r. \tag{3}$$

The wholesale price of w_n and w_r is firstly determined by the manufacturer, then the retail price of p_n and p_r is determined by the retailer. Therefore, the reverse induction method is used to solve the following results:

$$w_n^a = \frac{1}{4}\left(2Q + 2C_n - 2p_c u e_n + u^2 e_n^2 \gamma_n^2\right), \tag{4}$$

$$w_r^a = \frac{1}{4}\left(2\varepsilon Q + 2c_r + 2c_u - 2p_c u e_r + u^2 e_n^2 \gamma_n^2\right), \tag{5}$$

$$p_n^a = \frac{10Q + 2\varepsilon Q + 2c_n + 2c_r + 2c_u - 2p_c u e_n - 2p_c u e_r + u^2 e_n^2 \gamma_n^2 + u^2 e_r^2 \gamma_r^2}{12 + 4\varepsilon}, \tag{6}$$

$$p_r^a = \frac{2Q + 8\varepsilon Q + 2\varepsilon^2 Q - 2c_n + 4c_r + 2\varepsilon c_r + 4c_u + 2\varepsilon c_u + 2p_c u e_n - 4p_c u e_r - 2\varepsilon p_c u e_r - u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2 + \varepsilon u^2 e_r^2 \gamma_r^2}{12 + 4\varepsilon}, \tag{7}$$

$$D_n^a = -\frac{4Q - 2\varepsilon Q - 2\varepsilon^2 Q - 4c_n + 2c_r + 2\varepsilon c_r + 2c_u + 2\varepsilon c_u + 4p_c u e_n - 2p_c u e_r - 2\varepsilon p_c u e_r - 2u^2 e_n^2 \gamma_n^2 + u^2 e_r^2 \gamma_r^2 + \varepsilon u^2 e_r^2 \gamma_r^2}{4\varepsilon^2 + 8\varepsilon - 12}, \tag{8}$$

$$D_r^a = \frac{2Q - 2\varepsilon Q - 2c_n - 2\varepsilon c_n + 4c_r + 4c_u + 2p_c u e_n + 2\varepsilon p_c u e_n - 4p_c u e_r - u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2}{4\varepsilon^2 + 8\varepsilon - 12}. \tag{9}$$

Therefore, under the way of without government subsidies, the optimal pricing strategy is (w_n^a, w_r^a) and (p_n^a, p_r^a), and the product market demand is (D_n^a, D_r^a). At this point, the total carbon emission amount is $E^a = e_n D_n^a + e_r D_r^a$. At the same time, the total profits of manufacturers, retailers, and the entire supply chain system without government subsidies are easily calculated as follows:

$$\pi_M^a = \frac{AB + C\ D}{16\varepsilon^2 + 32\varepsilon - 48}, \tag{10}$$

$$\pi_R^a = \frac{AE + DF}{16(\varepsilon - 1)(\varepsilon + 3)^2}. \tag{11}$$

Among,

$$\begin{aligned}
A &= 2Q - 2\varepsilon Q - 2c_n - 2\varepsilon c_n + 4c_r + 4c_u + 2p_c u e_n + 2\varepsilon p_c u e_n - 4p_c u e_r - u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2,\\
B &= 2\varepsilon Q - 2c_r - 2c_u + 2p_c u e_r - u^2 e_r^2 \gamma_r^2,\\
C &= 2Q - 2c_n + 2p_c u e_n - u^2 e_n^2 \gamma_n^2,\\
D &= -4Q + 2\varepsilon Q + 2\varepsilon^2 Q + 4c_n - 2c_r - 2\varepsilon c_r - 2c_u - 2\varepsilon c_u - 4p_c u \varepsilon e_n + 2p_c u e_r + 2\varepsilon p_c u e_r + 2u^2 e_n^2 \gamma_n^2 - u^2 e_r^2 \gamma_r^2 - \varepsilon u^2 e_r^2 \gamma_r^2,\\
E &= 2Q + 2\varepsilon Q - 2c_n - 2c_r - 2c_u + 2p_c u e_n + 2p_c u e_r - u^2 e_n^2 \gamma_n^2 - u^2 e_r^2 \gamma_r^2,\\
F &= 4Q - 4c_n - 2\varepsilon c_n + 2c_r + 2c_u + 4p_c u e_n + 2\varepsilon p_c u e_n - 2p_c u e_r - 2u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_n^2 \gamma_n^2 + u^2 e_r^2 \gamma_r^2,\\
\pi_S^a &= \pi_M^a + \pi_R^a.
\end{aligned} \tag{12}$$

As a basic model, this section is compared with the follow-up model to reflect the role of government subsidies on the sales of remanufacturing products.

5. Decentralized Decisions under Different Subsidy Methods

5.1. Government Subsidies for the Manufacturer to Produce Remanufacturing Products. The government subsidizes the manufacturer to encourage the production of remanufacturing products. By solving the model, the impact of the production subsidy on the wholesale price and the sales price is analyzed, and the formula of subsidy to promote the production and sales of remanufacturing products is given.

Considering the government subsidies, the profit function of the manufacturer is set as follows:

$$\begin{aligned}
\pi_M^b = &\left(w_n - c_n - \frac{\gamma_n \mu^2 e_n^2}{2} + p_c u e_n\right) D_n\\
&+ \left(w_r - c_r - c_u - \frac{\gamma_r \mu^2 e_r^2}{2} + p_c u e_r + k_m\right) D_r.
\end{aligned} \tag{13}$$

The profit function of the retailer is set as follows:

$$\pi_R^b = (p_n - w_n) D_n + (p_r - w_r) D_r. \tag{14}$$

The following equations are derived by using the inverse induction method.

$$\begin{aligned}
w_n^b &= \frac{1}{4}\left(2Q + 2c_n - 2p_c u e_n + u^2 e_n^2 \gamma_n^2\right),\\
w_r^b &= \frac{1}{4}\left(-2k_m + 2\varepsilon Q + 2c_r + 2c_u - 2p_c u e_r + u^2 e_r^2 \gamma_r^2\right),
\end{aligned} \tag{15}$$

$$p_n^b = \frac{-2k_m + 10Q + 2\varepsilon Q + 2c_n + 2c_r + 2c_u - 2p_c u e_n - 2p_c u e_r + u^2 e_n^2 \gamma_n^2 + u^2 e_r^2 \gamma_r^2}{12 + 4\varepsilon}, \tag{16}$$

$$p_r^b = \frac{-4k_m - 2\varepsilon k_m + 2Q + 8\varepsilon Q + 2\varepsilon^2 Q - 2c_n + 4c_r + 2\varepsilon c_r + 4c_u + 2\varepsilon c_u + 2p_c u e_n - 4p_c u e_r - 2\varepsilon p_c u e_r - u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2 + \varepsilon u^2 e_r^2 \gamma_r^2}{12 + 4\varepsilon}, \tag{17}$$

$$D_r^b - \frac{-2k_m - 2\varepsilon k_m + 4Q - 2\varepsilon Q - 2\varepsilon^2 Q - 4c_n + 2c_r + 2\varepsilon c_r + 2c_u + 2\varepsilon c_u + 4p_c u e_r - 2p_c u e_r - 2\varepsilon p_c u e_r - 2u^2 e_n^2 \gamma_n^2 + u^2 e_r^2 \gamma_r^2 + \varepsilon u^2 e_r^2 \gamma_r^2}{4\varepsilon^2 + 8\varepsilon - 12}, \tag{18}$$

$$D_r^b = \frac{-4k_m + 2Q - 2\varepsilon Q - 2c_n - 2\varepsilon c_n + 4c_r + 4c_u + 2p_c u e_n + 2\varepsilon p_c u e_n - 4p_c u e_r - u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2}{4\varepsilon^2 + 8\varepsilon - 12}. \tag{19}$$

From equations (17), (19), and (21), the following conclusion can be drawn.

Conclusion 1. Under the way of government subsidies for the manufacturer to produce remanufacturing products, the optimal wholesale price of remanufacturing products has a negative proportional relationship with k_m and the trading price of unit carbon emission rights (p_c), and a positive proportional relationship with the investment coefficient of unit carbon emission reduction (γ_r). The optimal retail price of remanufacturing products has a negative proportional relationship with k_m, and a positive proportional relationship with the investment coefficient of unit carbon emission reduction (γ_r). The demand for remanufacturing products has a positive proportional relationship with k_m, and a negative proportional relationship with the investment coefficient of unit carbon emission reduction (γ_r).

This shows that when manufacturers receive subsidies, they will reduce the production burden of remanufacturing products, and accordingly the wholesale and retail prices will be lowered, and the lower prices will motivate more consumers to buy the products and subsequently increase the sales volume of remanufacturing products. Manufacturers will invest in emission reduction according to the carbon emissions at the time of production, and with the investment of capital, in order to ensure the revenue of enterprises, manufacturers will raise the wholesale prices, and the increase in the retail price will make consumers less motivated to buy products, which will reduce the demand for remanufacturing products. As a result of effective investment in carbon emission reduction, manufacturers will sell their surplus carbon credits to other companies, and the increase in the trading price of carbon emission rights will enable manufacturers to gain enough revenue to cut the wholesale price of their products, and accordingly retailers will cut the retail price.

According to Section 4, the demand formula (9) for remanufacturing products provided without government subsidies is compared with the demand for remanufacturing products under the government subsidies approach for the manufacturer to produce remanufacturing products, and the following conclusion can be drawn.

Conclusion 2. The formula for government subsidies to manufacturers to produce remanufacturing products to promote the production of remanufacturing products is $k_m/(1-\varepsilon)(\varepsilon+3)$. It can be seen that the promotion effect of subsidies on remanufacturing products is determined by k_m and ε jointly. This shows that when the government gives production subsidies, manufacturers can adjust the production of remanufacturing products according to the willingness of consumers to pay for remanufacturing products and the amount of subsidies.

Therefore, when the government subsidies the manufacturer for the production of remanufacturing products, the optimal pricing strategy is (w_n^b, w_r^b) and (p_n^b, p_r^b), and the market demand for products is (D_n^b, D_r^b). At this point, the total carbon emissions are $E^b = e_n D_n^b + e_r D_r^b$. At the same time, the total profits of manufacturers, retailers, and the entire supply chain system are easily gained under the way of government subsidies for the manufacturer, as shown in the following formulas:

$$\pi_M^b = \frac{A_1 B_1 + C\ D}{16\varepsilon^2 + 32\varepsilon - 48}, \tag{20}$$

$$\pi_R^b = \frac{A_1 E_1 + D_1 F_1}{16(\varepsilon - 1)(\varepsilon + 3)}. \tag{21}$$

Among them,

$$\begin{aligned}
A_1 &= -4k_m + 2Q - 2\varepsilon Q - 2c_n - 2\varepsilon c_n + 4c_r + 4c_u + 2p_c u e_n + 2\varepsilon p_c u e_n - 4p_c u e_r - u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2,\\
B_1 &- 2k_m + 2\varepsilon Q - 2c_r - 2c_u + 2p_c u e_r - u^2 e_r^2 \gamma_r^2,\\
C &= 2Q - 2c_n + 2p_c u e_n - u^2 e_n^2 \gamma_n^2,\\
D_1 &= 2k_m + 2\varepsilon k_m - 4Q + 2\varepsilon Q + 2\varepsilon^2 Q + 4c_n - 2c_r - 2\varepsilon c_r - 2c_u - 2\varepsilon c_u - 4p_c u e_n\\
&\quad + 2p_c u e_r + 2\varepsilon p_c u e_r + 2u^2 e_n^2 \gamma_n^2 - u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_r^2 \gamma_r^2,\\
E_1 &= 2k_m + 2Q + 2\varepsilon Q - 2c_n\\
F_1 &= -2k_m + 4Q - 4c_n - 2\varepsilon c_n\\
\pi_S^b &= \pi_M^b + \pi_R^b.
\end{aligned} \tag{22}$$

5.2. Government Subsidies for the Retailer to Sell Remanufacturing Products. The government gives sales subsidies for the retailer to encourage the sales volume of remanufacturing products. By solving the model, the effect of production subsidies on wholesale and sales prices is analyzed. Comparing the results with those of Section 5.1, it can be seen that which strategy is more beneficial to the production and sales of remanufacturing products.

Considering the government subsidies, the profit function of the manufacturer is set as follows:

$$\pi_M^c = \left(w_n - c_n - \frac{\gamma_n \mu^2 e_n^2}{2} + p_c u e_n\right) D_n + \left(w_r - c_r - c_u - \frac{\gamma_r \mu^2 e_r^2}{2} + p_c u e_r\right) D_r. \tag{23}$$

The profit function of the retailer is set as follows:

$$\pi_R^c = (p_n - w_n) D_n + (p_r - w_r + k_r) D_r. \tag{24}$$

The following equations are derived by using the inverse induction method:

$$w_n^c = \frac{1}{4}\left(2Q + 2c_n - 2p_c u e_n + u^2 e_n^2 \gamma_n^2\right), \tag{25}$$

$$w_n^c = \frac{1}{4}\left(2k_r + 2\varepsilon Q + 2c_r + 2c_u - 2p_c u e_r + u^2 e_r^2 \gamma_r^2\right), \tag{26}$$

$$p_n^c = \frac{-2k_r + 10Q + 2\varepsilon Q + 2c_n + 2c_r + 2c_u - 2p_c u e_n - 2p_c u e_r + u^2 e_n^2 \gamma_n^2 + u^2 e_r^2 \gamma_r^2}{12 + 4\varepsilon}, \tag{27}$$

$$p_n^c = \frac{-4k_r - 2\varepsilon k_r + 2Q + 8\varepsilon Q + 2\varepsilon^2 Q - 2c_n + 4c_r + 2\varepsilon c_r + 4c_u + 2\varepsilon c_u + 2p_c u e_n - 4p_c u e_r - 2\varepsilon p_c u e_r - u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2 + \varepsilon u^2 e_r^2 \gamma_r^2}{12 + 4\varepsilon}, \tag{28}$$

$$D_n^c = -\frac{-2k_r - 2\varepsilon k_r + 4Q - 2\varepsilon Q - 2\varepsilon^2 Q - 4c_n + 2c_r + 2\varepsilon c_r + 2c_u + 2\varepsilon c_u + 4p_c u e_n - 2p_c u e_r - 2\varepsilon p_c u e_r - 2u^2 e_n^2 \gamma_n^2 + u^2 e_r^2 \gamma_r^2 + \varepsilon u^2 e_r^2 \gamma_r^2}{4\varepsilon^2 + 8\varepsilon - 12}, \tag{29}$$

$$D_r^c = \frac{-4k_r + 2Q - 2\varepsilon Q - 2c_n - 2\varepsilon c_n + 4c_r + 4c_u + 2p_c u e_n + 2\varepsilon p_c u e_n - 4p_c u e_r - u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2}{4\varepsilon^2 + 8\varepsilon - 12}. \tag{30}$$

From equations (28), (30), and (32), the following conclusion can be drawn.

Conclusion 3. Under the way of government subsidies for the retailer to sell remanufacturing products, the optimal wholesale price of remanufacturing products is positively proportional to k_r and the investment coefficient of unit carbon emission reduction (γ_r), and negatively proportional to the trading price of unit carbon emission reduction (p_c). The optimal retail price of remanufacturing products is negatively proportional to $k_r$and positively proportional to the investment coefficient of unit carbon emission reduction (γ_r). The demand for remanufacturing products is positively proportional to $k_r$and negatively proportional to the investment coefficient of unit carbon emission reduction (γ_r).

This shows that after receiving subsidies, retailers will consider lowering the retail price of products. The lower retail price will encourage more consumers to buy products and then increase the demand for remanufacturing products, but manufacturers will increase the wholesale price of remanufacturing products due to the subsidy policy and the production cost of the unit product.

According to Section 4, the demand formula (9) for remanufacturing products provided without government subsidies is compared with the demand for remanufacturing products under the government subsidies approach for the retailer to sell remanufacturing products, and the following conclusion can be drawn.

Conclusion 4. The formula for government subsidies for retailers to sell remanufacturing products to promote sales of remanufacturing products is $k_r/(1-\varepsilon)(\varepsilon+3)$. It can be seen

Table 1: Optimal decision for remanufacturing products in different ways.

Decision variables	Without government subsidies	Production subsidies	Sale subsidies	Centralized decision-making
w_n	260.66	260.66	260.66	
w_r	110.29	109.79	110.79	
p_n	403.22	403.07	403.07	306.14
p_r	207.07	206.71	206.71	213.43
D_n	173.08	172.74	172.74	345.47
D_r	76.30	75.81	75.81	151.61
E	6336.80	6319.15	6319.15	
π_M	34579.50	34503.40	34503.40	
π_R	17289.70	17251.70	17251.70	
π_S	51869.20	51755.10	51755.10	69006.90

that the promotion effect of subsidies on remanufacturing products is determined by k_r and ε jointly. This shows that when the government gives sales subsidies, manufacturers can adjust the production of remanufacturing products according to the willingness of consumers to pay for remanufacturing products and the amount of subsidies.

Therefore, when the government subsidies retailers to sell remanufacturing products, the optimal pricing strategy for products is (w_n^c, w_r^c) and (p_n^c, p_r^c), and the market demand for products is (D_n^c, D_r^c). At this point, the total carbon emissions are $E^c = e_n D_n^c + e_r D_r^c$. At the same time, the total profits of manufacturers, retailers, and the entire supply chain system are easily gained under the way of government subsidies for the retailer, as shown in the following formulas:

$$\pi_M^c = \frac{A_2 B_2 + C D_2}{16\varepsilon^2 + 32\varepsilon - 48}, \tag{31}$$

$$\pi_R^c = \frac{A_2 E_2 + D_2 F_2}{16(\varepsilon - 1)(\varepsilon + 3)}. \tag{32}$$

Among them,

$$\begin{aligned}
A_2 &= -4k_r + 2Q - 2\varepsilon Q - 2c_n - 2\varepsilon c_n + 4c_r + 4c_u + 2p_c u e_n + 2\varepsilon p_c u e_n - 4p_c u e_r - u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2,\\
B_2 &= 2k_r + 2\varepsilon Q - 2c_r - 2c_u + 2p_c u e_r - u^2 e_r^2 \gamma_r^2,\\
C &= 2Q - 2c_n + 2p_c u e_n + u^2 e_n^2 \gamma_n^2,\\
D_2 &= 2k_r + 2\varepsilon k_r - 4Q + 2\varepsilon Q + 2\varepsilon^2 Q + 4c_n - 2c_r - 2\varepsilon c_r - 4p_c u e_n + 2p_c u e_r + 2\varepsilon p_c u e_r + 2u^2 e_n^2 \gamma_n^2 - u^2 e_r^2 \gamma_r^2 - \varepsilon u^2 e_r^2 \gamma_r^2,\\
E_2 &= 2k_r + 2Q + 2\varepsilon Q - 2c_n - 2c_r - 2c_u + 2p_c u e_n + 2p_c u e_r - u^2 e_n^2 \gamma_n^2 - u^2 e_r^2 \gamma_r^2,\\
F_2 &= -2k_r + 4Q - 4c_n - 2\varepsilon c_n + 2c_r + 2c_u + 4p_c u e_n + 2\varepsilon p_c u e_n - 2p_c u e_r - 2u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_n^2 \gamma_n^2 + u^2 e_r^2 \gamma_r^2,\\
\pi_S^c &= \pi_M^c + \pi_R^c.
\end{aligned} \tag{33}$$

5.3. Comparative Analysis of the Two Subsidy Methods. Since the expressions for the optimal retail price and demand for remanufacturing products are the same for both approaches (except that k_m differs from k_r), it can be seen that the government subsidizes the manufacturer of remanufacturing products and subsidizes the retailer of remanufacturing products, and the two subsidy approaches are equivalent in promoting the sales of remanufacturing products, so it can be assumed that $k_m = k_r$.

From the hypothesis of $k_m = k_r$, comparing and analyzing the way the government subsidizes for the manufacturer to produce remanufacturing products (5.1) and the way the government subsidizes for the retailer to sell remanufacturing products (5.2), the results are obtained: $w_n^b = w_n^c$, $D_n^b = D_n^c$, $p_n^b = p_n^c$, $p_r^b = p_r^c$, $D_r^b = D_r^c$, $w_r^c - w_r^b = 1/2k_r + 1/2k_m = k_m$, $\pi_M^b = \pi_M^c$, $\pi_R^b = \pi_R^c$, and $\pi_S^b = \pi_S^c$. The following conclusion can be drawn from the above results.

Conclusion 5. The optimal retail price and demand of remanufacturing products will not change with the government subsidy method, which means that the two subsidy methods will promote the production and sales of remanufacturing products equally. At the same time, the wholesale price set by the manufacturer when the government subsidizes the manufacturer to produce remanufacturing products is less than the wholesale price set by the manufacturer when the government subsidizes the retailer to sell remanufacturing products, and the difference between the two is exactly equal to the amount of government subsidy per unit of the manufacturer to produce remanufacturing products remanufacturing products (k_m). Moreover, the profits of manufacturers, retailers, and the whole supply chain system do not change under the two different subsidy methods, which indicates that no matter which

subsidy method is used, manufacturers can adjust the wholesale price of remanufacturing products to achieve the goal of balancing the profits of the whole supply chain system.

6. Government Subsidies in Centralized Decision-Making

In the way of government subsidies in centralized decision-making, the manufacturer cooperates with the retailer to set the optimal selling price of products and shares the benefits of government subsidies for remanufacturing products.

The total profit of the supply chain system is set as follows:

$$\pi_S^d = \left(p_n - c_n - \frac{\gamma_n \mu^2 e_n^2}{2} + p_c u e_n\right) D_n + \left(p_r - c_r - c_u - \frac{\gamma_r \mu^2 e_r^2}{2} + p_c u e_r\right) D_r. \tag{34}$$

The following equations are derived by analyzing the decision of the entire supply chain system:

$$p_n^d = \frac{-2k + 4Q + 2c_n + 2c_r + 2c_u - 2p_c u e_n - 2p_c u e_r + u^2 e_n^2 \gamma_n^2 + u^2 e_r^2 \gamma_r^2}{6 + 2\varepsilon}, \tag{35}$$

$$p_r^d = \frac{-4k - 2\varepsilon k + 2Q + 2\varepsilon Q - 2c_n + 4c_r + 2\varepsilon c_r + 4c_u + 2\varepsilon c_u + 2p_c u e_n - 4p_c u e_r - 2\varepsilon p_c u e_r - u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2 + \varepsilon u^2 e_r^2 \gamma_r^2}{6 + 2\varepsilon}, \tag{36}$$

$$D_n^d = -\frac{-2k - 2\varepsilon k + 4Q - 2\varepsilon Q - 2\varepsilon^2 Q - 4c_n + 2c_r + 2\varepsilon c_r + 2c_u + 2\varepsilon c_u + 4p_c u e_n - 2p_c u e_r - 2\varepsilon p_c u e_r - 2u^2 e_n^2 \gamma_n^2 + u^2 e_r^2 \gamma_r^2 + \varepsilon u^2 e_r^2 \gamma_r^2}{2\varepsilon^2 + 4\varepsilon - 6}, \tag{37}$$

$$D_r^d = \frac{-4k + 2Q - 2\varepsilon Q - 2c_n - 2\varepsilon c_n + 4c_r + 4c_u + 2p_c u e_n + 2\varepsilon p_c u e_n - 4p_c u e_r - u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2}{2\varepsilon^2 + 4\varepsilon - 6}. \tag{38}$$

From (36) and (38), the following conclusion can be drawn.

Conclusion 6. Under the way of government subsidy at the time of centralized decision-making, the optimal retail price of remanufacturing products has a negative proportional relationship with k, and a positive proportional relationship with the investment coefficient of unit carbon emission reduction (γ_r). The demand for remanufacturing products has a positive proportional relationship with k, and a negative proportional relationship with the investment coefficient of unit carbon emission reduction (γ_r).

This shows that when manufacturers and retailers cooperate to obtain subsidies, they will lower the retail price of remanufacturing products, and the lower price will motivate more consumers to buy the products, and subsequently increase the sales volume of remanufacturing products. Manufacturers will invest in emission reduction according to the carbon emissions at the time of production, and in order to ensure their own profit, manufacturers and retailers will increase the retail price, and the increase in retail price will make consumers. Due to the effective investment of carbon emission reduction, manufacturers will sell the remaining carbon emission rights to other enterprises, and the increase of carbon emission rights trading price will make manufacturers gain enough revenue to cut the retail price.

Therefore, when the government subsidies retailers for selling remanufacturing products, the optimal pricing strategy of the product is (p_n^d, p_r^d), and the product market demand is (D_n^d, D_r^d). At the same time, the total profit of the supply chain system when the government subsidizes centralized decisions is easily gained, as shown in the following formula:

$$\pi_S^d = \frac{A_3 E_3 + D_3 F_3}{3(\varepsilon - 1)(\varepsilon + 3)^2}. \tag{39}$$

Among them,

$$A_3 = -4k + 2Q - 2\varepsilon Q - 2c_n - 2\varepsilon c_n + 4c_r + 4c_u + 2p_c u e_n + 2\varepsilon p_c u e_n - 4p_c u e_r - u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_n^2 \gamma_n^2 + 2u^2 e_r^2 \gamma_r^2,$$
$$D_3 = 2k + 2\varepsilon k - 4Q + 2\varepsilon Q + 2\varepsilon^2 Q + 4c_n - 2c_r - 2\varepsilon c_r - 2c_u - 2\varepsilon c_u - 4p_c u e_n + 2p_c u e_r + 2\varepsilon p_c u e_r + 2u^2 e_n^2 \gamma_n^2 - u^2 e_r^2 \gamma_r^2 - \varepsilon u^2 e_r^2 \gamma_r^2,$$
$$E_3 = 2k + 2Q + 2\varepsilon Q - 2c_n - 2c_r - 2c_u + 2p_c u e_n + 2p_c u e_r - u^2 e_n^2 \gamma_n^2 - u^2 e_r^2 \gamma_r^2,$$
$$F_3 = -2k + 4Q - 4c_n - 2\varepsilon c_n + 2c_r + 2c_u + 4p_c u e_n + 2\varepsilon p_c u e_n - 2p_c u e_r - 2u^2 e_n^2 \gamma_n^2 - \varepsilon u^2 e_n^2 \gamma_n^2 + u^2 e_r^2 \gamma_r^2. \quad (40)$$

Comparing decentralized decisions (Sections 5.1 and 5.2) and centralized decisions, the results are obtained: $p_n^b = p_n^c > p_n^d$, $D_n^b = D_n^c < D_n^d$, $p_r^b = p_r^c < p_r^d$, $D_r^b = D_r^c < D_r^d$, and $\pi_S^b = \pi_S^c < \pi_S^d$. The following conclusion can be drawn from the above results.

Conclusion 7. Compared with the way that the government only subsidizes manufacturers or retailers, under the centralized decision-making, the retail price of remanufacturing products increases, the sales volume increases, and the total profit of the whole supply chain is optimized. This indicates that under the centralized decision-making, manufacturers and retailers can actively coordinate their respective target decisions through information exchange and sharing so that the profit of the whole remanufacturing product supply chain system can be optimized and the profit loss caused by "double marginal effect" in the remanufacturing product supply chain can be reduced.

7. Numerical Simulation

Combined with the current situation of the remanufacturing industry and some related literature [7, 11], the values of the parameters are taken as follows: $c_n = 20$ (*yuan*), $c_r = 10$ (*yuan*), $c_u = 5$ (*yuan*), $e_n = 30$ (kg), $e_r = 15$ (kg), $\gamma_n = 0.5$, $\gamma_r = 0.3$, $\lambda = 0.4$, $\mu = 0.2$, $Q = 500$ (*piece*), $\varepsilon = 0.4$ and $k_m = k_r = k = 1$ (*yuan*). According to relevant statistical data, the average price of the national carbon quota in the first week of July 2021 is 36.09 (*yuan/ton*). Therefore, this study takes $p_c = 0.05$ (*yuan/kg*).

7.1. Comparison of Various Decision Variables, the Product Market Demand, the Profits of Supply Chain Members, and System in Different Ways. The optimal decision variables for remanufacturing products in different ways are shown in Table 1.

As can be seen from Table 1, the wholesale price of the remanufacturing product is the largest under the sales subsidy approach, and a comparison with the production subsidy approach reveals that the wholesale price differs by 1, which is exactly the value of k. The retail price of remanufacturing products is the largest when the decision is centralized, and the values are equal under the production subsidy and sales subsidy. The demand of remanufacturing products is the largest when the decision is centralized, and the demand is the same under the production subsidy and sales subsidy. The total carbon emission of the manufacturer is the smallest under the production subsidy and sales subsidy methods, which shows that after the government subsidy, the manufacturer will actively invest new technology and new resources into carbon emission reduction, thus reducing the total carbon emission. The profit of the manufacturer and the retailer is the same under the production subsidy and sales subsidy, and it is higher than the profit without the government subsidy. The profit of the whole remanufacturing supply chain system is the largest under the centralized decision. The profit of the whole remanufacturing supply chain system is the largest when the decision is centralized, and the profit is the same under the production subsidy and sales subsidy methods. This is because when the decision is centralized, manufacturers and retailers can actively coordinate their target decisions through information exchange and sharing so that the profit of the whole remanufacturing product supply chain system can be optimized. This verifies the correctness of Conclusions 5 and 7.

7.2. Impact of the Trading Price of Unit Carbon Emission Rights on Various Decision Variables and Optimal Profit. The effects of the trading price of unit carbon emission rights on each decision variable and optimal profit are discussed in depth here. Let $p_c \in (0, 1)$, the values of the above-given parameters are substituted into the equations in Sections 5 and 6, and the effects of the changes in the trading price of unit carbon emission rights on the wholesale price, retail price, demand, and optimal profit of remanufacturing products under the production subsidy are obtained, as shown in Figures 3 and 4.

According to Figure 3, the wholesale price and retail price of remanufacturing products decreases with the increase of the trading price of unit carbon emission rights. The demand of remanufacturing products increases with the increase of the trading price of unit carbon emission rights. This shows that due to the effective investment in carbon reduction, manufacturers will sell the remaining carbon emissions to other enterprises, the trading price of unit carbon emission rights will make manufacturers get enough revenue to reduce the wholesale prices, and corresponding retailers will cut the retail price of remanufacturing products. Lower prices will prompt more consumers to buy products, which in turn increases the demand for remanufacturing products. This is consistent with parts of Conclusions 1, 3, and 6.

From Figure 4, the profits of manufacturers and retailers increase with the price of the trading price of unit carbon emission rights. This shows that due to the effective investment of carbon emission reduction, manufacturers will sell the remaining carbon rights to other companies, and get

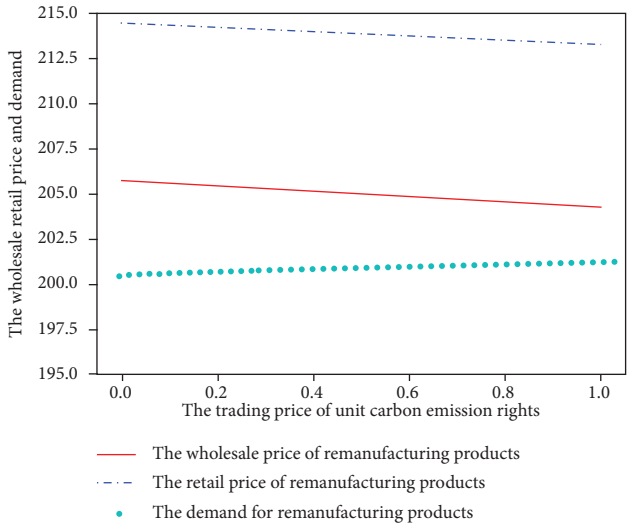

Figure 3: The effect of the trading price of unit carbon emission rights on the wholesale price, retail price, and demand of remanufacturing products.

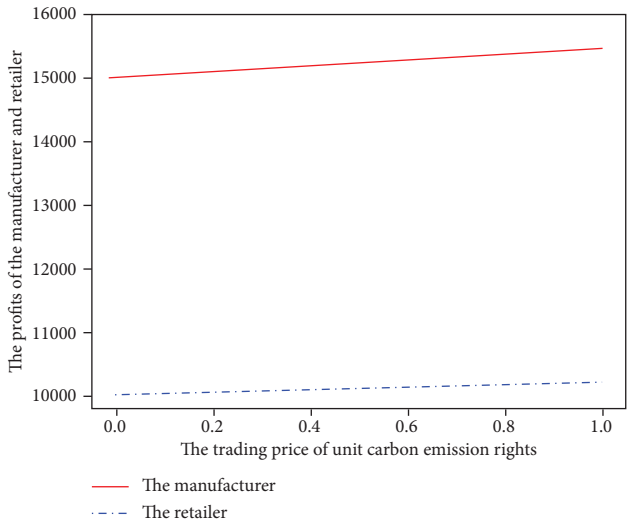

Figure 4: The effect of the trading price of unit carbon emission rights on the profits of the manufacturer and retailer.

enough revenue through higher trading prices, as well as lower wholesale and retail prices. The lower price will encourage more consumers to buy products, then increase the sales volume of remanufacturing products. Finally, the sales volume make manufacturers and retailers get more profits.

7.3. Impact of the Emission Reduction Target Coefficient on Each Decision Variable and Optimal Profit. The effects of the emission reduction target coefficient on each decision variable and optimal profit are discussed in depth here. Let $\mu \in (0, 1)$, the values of the above-given parameters are substituted into the equations in Sections 5 and 6, and the effects of the changes in the emission reduction target coefficient on the wholesale price, retail price, demand, and optimal profit of remanufacturing products under the production subsidy are obtained, as shown in Figures 5 and 6.

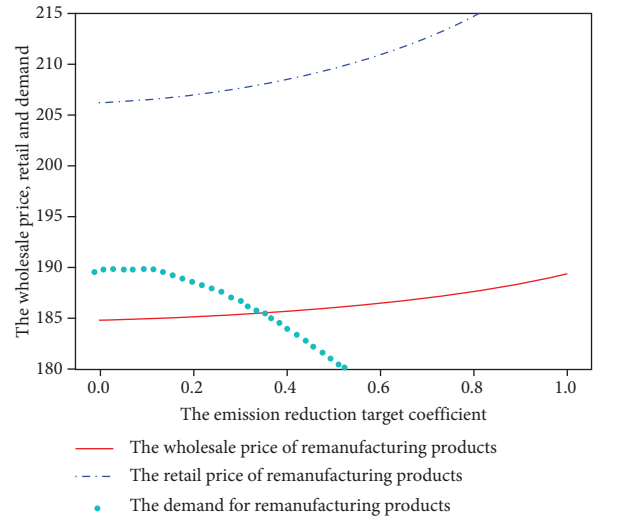

Figure 5: The impact of the emission reduction target coefficient on the wholesale price, retail price, and demand of manufactured products.

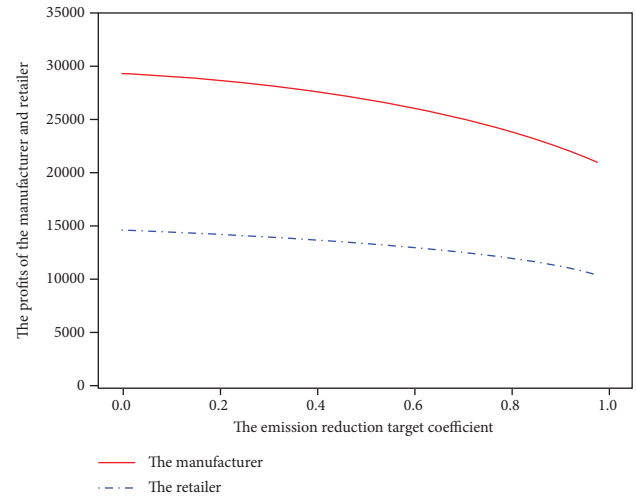

Figure 6: The impact of the emission reduction target coefficient on the profits of the manufacturer and retailer.

From Figure 5, the wholesale price and retail price of remanufacturing products increases with the increase of the emission reduction target coefficient. The demand of remanufacturing products decreases with the increase of the emission reduction target coefficient. This shows that the increase of the emission reduction target coefficient means that manufacturers bear higher emission reduction costs, so that they will increase the wholesale price of remanufacturing products, and retailers will accordingly increase the retail price of products. The increase in price will reduce the enthusiasm of consumers to buy products, which in turn reduces the demand for remanufacturing products. This is consistent with parts of Conclusions 1, 3, and 6.

From Figure 6, both the profits of manufacturers and retailers decrease with the emission reduction target coefficient. This shows that the increase of the emission reduction target coefficient, manufacturers will bear higher

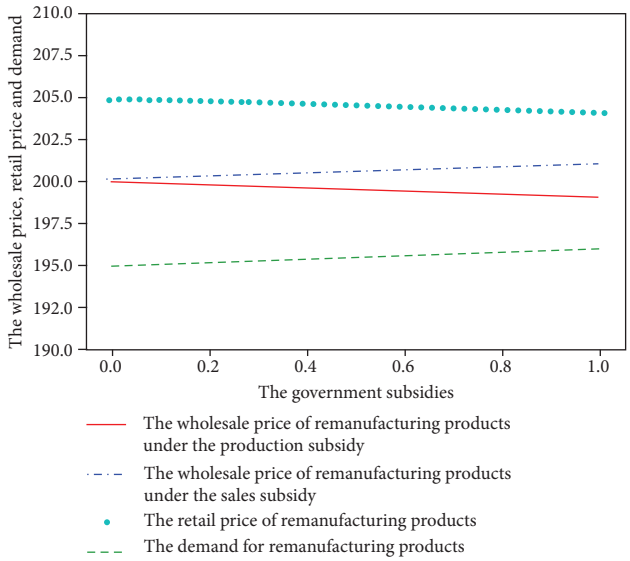

Figure 7: The influence of government subsidies on the wholesale price, retail price, and demand of remanufacturing products.

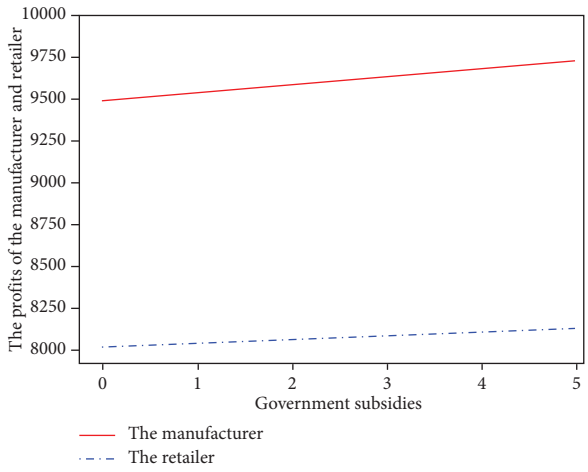

Figure 8: The influence of government subsidies on the profits of the manufacturer and retailer.

emission reduction costs, so manufacturers will increase the wholesale price of remanufacturing products, and retailers will increase the retail price. Rising prices will reduce the enthusiasm of consumers to buy remanufacturing products, and then reduce the demand, which makes manufacturers and retailers lose some profits.

7.4. Impact of Government Subsidies on Various Decision Variables and Optimal Profits. The effects of government subsidies on each decision variable and optimal profit are discussed in depth here. Let $k \in (0, 5)$, the values of the above parameters are substituted into the equations in Sections 5 and 6, and the effects of the changes in the government subsidies on the wholesale price, retail price, demand, and optimal profit of remanufacturing products under the production subsidy are obtained, as shown in Figures 7 and 8.

From Figure 7, the wholesale price of remanufacturing products decreases with the increase of government subsidies under the production subsidy; under the sale subsidy, the wholesale price of remanufacturing products increases with the increase of government subsidies. The retail price of remanufacturing products decreases with the increase of government subsidies. The demand of remanufacturing products increases with the increase of government subsidies. This shows that when the manufacturer reduces the production burden of remanufacturing products, the wholesale and retail prices will reduce the retail price of products, but the manufacturer will still raise the wholesale price of remanufacturing products due to the subsidy policy and the product production cost. Lower retail prices will prompt more consumers to buy products, which in turn increases the demand for remanufacturing products. This is consistent with parts of Conclusions 1, 3, and 6.

In Figure 8, both the profits of manufacturers and retailers increase with government subsidies. This shows that government subsidies will reduce retail prices, which encourages more consumers to buy products, increasing the sales volume of manufactured products. Finally, manufacturers and retailers will get more profits.

7.5. Impact of the Investment Coefficient of Unit Carbon Emission Reduction on Each Decision Variable and the Optimal Profit. The effects of the investment coefficient of unit carbon emission reduction on each decision variable and optimal profit are discussed in depth here. Let $\gamma_n = \gamma_r \in (0, 1)$, the values of the above parameters are substituted into the equations in Sections 5 and 6, and the effects of the changes in the investment coefficient of unit carbon emission reduction on the wholesale price, retail price, demand, and optimal profit of remanufacturing products under the production subsidy are obtained, as shown in Figures 9 and 10.

According to Figure 9, the wholesale price and retail price of remanufacturing products increase with the investment coefficient of unit carbon emission reduction. The demand of remanufacturing products increase with the investment coefficient of unit carbon emission reduction. This shows that no matter what kind of subsidy, manufacturers will invest in emission reduction according to the carbon emissions during production. In order to ensure their own income, manufacturers will increase the wholesale price of remanufacturing products, and retailers will also increase the retail price of products. The rise in prices will reduce the enthusiasm of consumers to buy and remanufacture products, which in turn reduces demand. This is consistent with parts of Conclusions 1, 3, and 6.

From Figure 10, it can be seen that the profits of manufacturers and retailers both decrease with the increase of the investment coefficient of unit carbon emission reduction. This shows that manufacturers will make emission reduction investment according to the carbon emissions during production. The increase of emission reduction investment will increase the retail price, and the increase of retail price will reduce the enthusiasm of consumers to buy

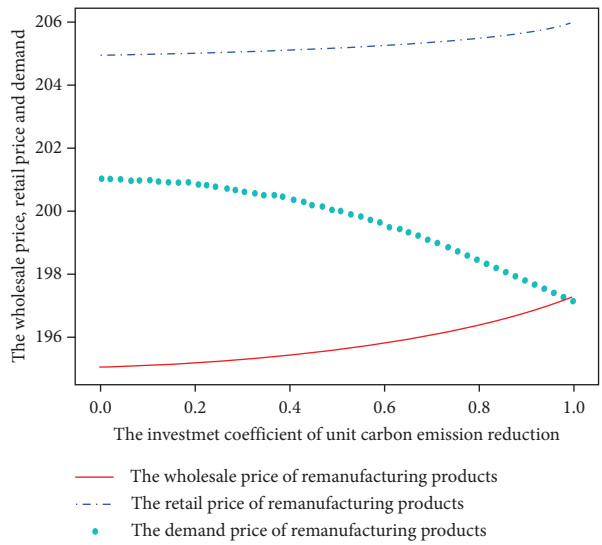

Figure 9: The effect of the investment coefficient of unit carbon emission reduction on the wholesale price, retail price, and demand of remanufacturing products.

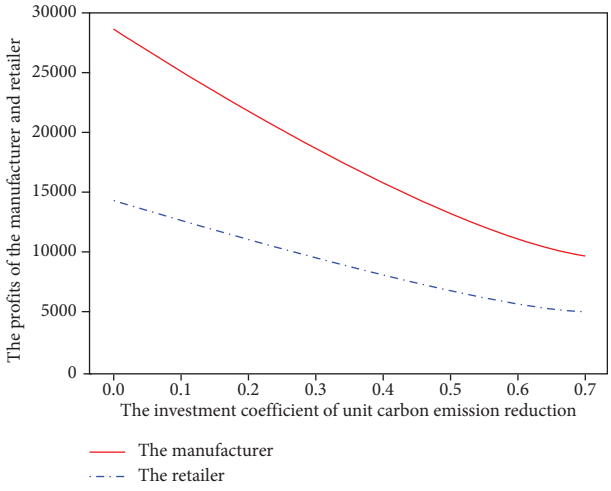

Figure 10: The effect of the investment coefficient of unit carbon emission reduction on the profits of the manufacturer and retailer.

products and then reduce the sales volume of remanufacturing products. The decrease of sales volume will make manufacturers and retailers lose some profits.

8. Conclusion and Implication

In this paper, we discussed in depth the influence of government subsidies on the optimal pricing decision of remanufacturing products in a carbon trading environment by establishing a Stackelberg game model consisting of retailers and manufacturers under four different subsidies and analyzed the effect of some key factors on the pricing decision of remanufacturing products through Python software. The study shows that

(1) Regardless of the subsidy method, the optimal wholesale price of remanufacturing products increases with the increase of investment coefficient and emission reduction target coefficient per unit of carbon emission reduction and decreases with the increase of trading price per unit of carbon emission rights; the optimal retail price of remanufacturing products decreases with the increase of government subsidies and trading price per unit of carbon emission rights and increases with the increase of investment coefficient and emission reduction target coefficient per unit of carbon emission reduction. The profits of manufacturers, retailers, and the whole supply chain system increase with the increase of government subsidies and unit carbon emission trading price and decrease with the increase of investment coefficient and emission reduction target coefficient of unit carbon emission reduction.

(2) Under the production subsidy approach, the optimal wholesale price of remanufacturing products decreases with the increase of government subsidies; under the sales subsidy approach, the optimal wholesale price of remanufacturing products increases with the increase of government subsidies.

(3) The government's promotion effect on the production and sales of remanufacturing products is the same under the two subsidy mechanisms of production subsidy and sales subsidy. Moreover, under the two different approaches, manufacturers can adjust the wholesale price of remanufacturing products to balance the profit of the whole remanufacturing supply chain system.

(4) Compared with the two ways of government subsidies for manufacturers or retailers, under the centralized decision, the sales volume increases, and the profit of the whole supply chain system is optimized. This indicates that under the centralized decision-making, manufacturers and retailers can actively coordinate their respective target decisions through information exchange and sharing so that the profit of the whole remanufacturing product supply chain system can be optimized and the profit loss caused by "double marginal effect" in the remanufacturing product supply chain can be reduced.

In order to make better pricing decisions for remanufacturing products and promote the development of a green low-carbon recycling economy, this paper proposes the following suggestions.

8.1. Improving the Carbon Trading System. The government should improve the carbon trading market laws and regulations, establish carbon trading organizations and management agencies, implement the main responsibility system of enterprises, and effectively perform its supervisory duties in order to effectively promote the healthy operation of the carbon trading market. At the same time, it should choose appropriate methods and emission factors to calculate CO_2 emissions according to the characteristics of different types of enterprises, so as to provide a solid foundation for enterprises to participate in the carbon trading market.

8.2. Setting Reasonable Carbon Emission Reduction Targets. With the increase of emission reduction target coefficients, the profits of manufacturers, retailers, and the whole supply chain system will decline. Therefore, the government should appropriately reduce the emission reduction targets according to the development of manufacturing enterprises to reduce the burden of emission reduction investment of manufacturing enterprises, so as to improve the profits of the supply chain and make the market reach a balanced state.

8.3. Building a Reasonable Subsidy Mechanism for Remanufacturing Products. The effect of government subsidies on the sales volume of remanufacturing products is jointly determined by the amount of subsidies and the price sensitivity coefficient of consumers to the products. Therefore, on the one hand, the government can guide for local governments' subsidy policies according to the three key points of "manufacturers and retailers with conditions," "recycling and remanufacturing" and "purchasing remanufacturing products at the same time." On the one hand, the government can provide guidance for local governments' subsidy policies to effectively expand the market scale of remanufacturing products. On the other hand, government subsidies to consumers can, to a certain extent, stimulate their demand for remanufacturing products, which will increase the sales of remanufacturing products accordingly.

8.4. Reducing Carbon Emission Reduction Investment. The reduction of costs of carbon emission reduction will enable manufacturers to reduce the wholesale price, and the reduction of price can increase the sales of products, thus improving the profit of the whole supply chain system. Therefore, manufacturers can reduce their own carbon emission reduction investment by adopting new technologies, choosing efficient carbon emission reduction facilities, adopting new environmentally friendly new energy sources, introducing high-level professionals in low-carbon production, providing low-carbon training for production workers, improving the technical level of workers in the production process, and setting up professional low-carbon management departments.

The shortcomings of this paper are as follows: (1) the market competition between new and remanufacturing products is not considered, while in the actual process, consumers will choose between the two products and (2) after the government subsidizes the cooperation between manufacturers and retailers, the profit distribution between them is not considered. Therefore, based on the existing research, product competition and profit coordination can be considered as the future research direction.

Data Availability

Combined with the current situation of the remanufacturing industry and some related literature [7] and [11], the values of the parametare taken. According to relevant statistical data, the average price of national carbon quota in the first week of July 2021 is 36.09 (yuan/ton).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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