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A Study on Remanufacturing Supply Chain Decision-Making Considering Greenness Under Carbon Trading Policy

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Abstract: The aim of this paper is to study the impact of carbon trading system and product greenness on remanufacturing strategy, so a Stackelberg game model is constructed to consider a remanufacturing supply chain consisting of a manufacturer and a third-party remanufacturer under carbon trading policy. Through theoretical analysis and numerical simulation, the relationship between decision variables such as product greenness, price of new products and remanufactured products is analyzed. It is found that: the level of carbon emission reduction is conducive to increase the price of new products and remanufactured products; under certain conditions, a stronger green market demand is conducive to increase the greenness of the products and the profits and prices of the remanufacturing supply chain members; an increase in the investment in green technology will lead to a decrease in the manufacturer's profit and the greenness of the products, and even reduce the price of the products under certain conditions; and under certain conditions, the carbon trading price is effective in regulating the price of new products and the price of the products. Under certain conditions, the carbon trading price can effectively regulate the price of new products and remanufactured products, while the greenness of products will decrease with the increase of carbon trading price.

Keywords: Stackelberg game, Carbon trading, Remanufacturing, Greenness.

1. Introduction

In recent years, along with the rapid development of the economy, environmental problems are facing serious challenges for the world, and the world is increasingly concerned about environmental problems. In order to actively deal with environmental problems, many countries have put forward relevant policies to control carbon emissions, such as carbon tax, carbon trading policies, etc. [3] Carbon trading policy is considered to be the best way for countries to implement carbon tax and carbon trading policy. Carbon trading policy is considered to be the most effective emission reduction policy implemented by various countries, which means that the government allocates a certain amount of carbon emission credits to enterprises, and enterprises can sell or buy carbon emission credits in the carbon trading market. As a strategic emerging industry, remanufacturing has a significant role in energy saving, resource recycling, carbon emission reduction, etc. Its kernel is the process of repairing and mass production of damaged or end-of-life used products through specialized processes and technologies. Compared with new products, remanufactured products are no less important than new products in terms of performance and quality. According to complete statistics, through the recycling of old products for remanufacturing can save 70% of the raw materials and 60% of the energy, but also can effectively reduce pollution emissions, to obtain considerable economic benefits. For example, Kodak recycles an average of 76% of its disposable cameras each year for use in the manufacture of new cameras. Volkswagen saves 70% on manufacturing costs by recycling engines and parts [11]. As a large carbon emitting country, China has been committed to promoting industrial structure upgrading, low-carbon transformation, put forward the "dual-carbon" goal, driven by the dual-carbon goal, the ecological environment continues to improve and optimize, green technology is also constantly innovating, the concept of green consumption is also gradually expanding. Consumers will also pay attention to the degree of environmental protection and greenness of the products when they consume [9]. Research shows that most consumers are concerned about the environmental friendliness and greenness of products when they consume. Research shows that most consumers consider buying green products because they help reduce environmental pollution [15]. When consumers buy green products, they are influenced by their own green demands, which depend on their own environmental concerns. When a company's environmental concern matches consumers' green demands, it will enhance consumers' concern for the company's green products and stimulate them to learn more about green products [16]. When the enterprise's environmental concern matches with consumers' green demands, it will enhance consumers' attention to the enterprise's green products and stimulate them to know more about green products. When enterprises pay attention to environmental standards and adopt corresponding green design behaviors, they can promote enterprises to carry out green recycling actions, and specific green recycling in place can effectively improve the environmental performance of enterprises. In the face of the enterprise meets the standard and perfect green recycling action, the environmental concern degree of consumers will be more willing to participate in green recycling, and promote the development of enterprise green recycling [17]. The development of green recycling by enterprises will be promoted.

In order to promote sustainability, scholars have conducted in-depth discussions on consumers' green preferences and remanufacturing supply chains. zhou et al. refer to the CEA and product greenness, which provide a reference for more scientific determination of product greenness and price [18]. Liu et al. studied the decision-making behavior of manufacturers and retailers in considering government subsidies to increase product greenness [20]. Aslani and Heydari et al. suggested that consumer awareness and preference for green products will influence consumer behavior [21, 23]. Yang et al. suggest that consumer behavior has a strong influence on manufacturers' decisions to green their products [22]. Yi et al. suggest that more and more consumers prefer to buy green products that are pollution-free and environmentally friendly, which results in green products that are more competitive than traditional products [19]. However, some scholars such as Xu et al. However, some scholars such as Xu et al. suggest that consumers have different levels of market demand for new and remanufactured products due to different consumption tendencies and cognitive levels. Although there is no difference in quality between new and remanufactured products, consumers have different recognition and willingness to pay for remanufactured products with the same quality and functions [14]. Hao constructed a secondary supply chain to address the problem of low consumer recognition of remanufactured products, and investigated how remanufacturers should adopt appropriate promotional strategies and pricing issues [28]. Hao constructed a secondary supply chain to address the problem of low consumer acceptance of remanufactured products. Carbon trading policies are also a hot topic of research, and Huang et al. argue that stricter regulations such as cap-and-trade or carbon taxes would encourage manufacturers to reduce waste [25]. Bikash et al. consider a pricing strategy under carbon regulations and show that investment in green technology can lead to increased profits [24]. Dai et al. considered the choice of carbon reduction and pricing strategies for manufacturers under a carbon trading policy, and showed that only cooperating to reduce emissions may be a suboptimal strategy from a comprehensive perspective [26]. Dai et al. consider a manufacturer's carbon reduction and pricing strategy options under a carbon trading policy. Considering consumers' low carbon awareness, Xu et al. developed a manufacturer-led game model. The conclusion suggests that the optimal abatement strategy for manufacturers is dynamic, and that they can increase their carbon abatement inputs to improve their investment profits when consumers' low-carbon preference is low and the government implements a cap-and-trade policy [27].

To summarize, although the above studies have discussed carbon trading policy, remanufacturing supply chain and product greenness in depth, the existing studies have not yet explored the relationship between carbon trading policy, product greenness and remanufacturing supply chain decision-making. Therefore, this paper constructs a game model, aiming to provide theoretical basis as well as reference for the decision-making choices of remanufacturing supply chain in the context of considering greenness and carbon trading policy.

2. Problem Description and Assumptions

2.1. Description of the Problem

Consider a re-supply chain consisting of a manufacturer, a third-party re-manufacturer under a carbon trading policy. In order to accurately describe the research problem, Table 1 summarizes the variables and parameters to be applied in the model. Among them. The manufacturer produces new products and licenses the remanufacturing business to the third-party remanufacturer, the manufacturer is subject to the government-led carbon trading policy due to its high carbon emission and energy consumption, and the government allocates free carbon credits to the manufacturer in a single cycle e_m and, if necessary, at a unit price p_c Carbon credits can be purchased or sold. Third-party manufacturers that recycle used products for remanufacturing are not directly constrained by government-led carbon trading policies due to their low-carbon emission and low-cost advantages, but due to market competition, carbon trading policies also indirectly affect the production and pricing decisions of third-party remanufacturers [3].

The manufacturer, as the dominant player in the supply chain, determines the level of carbon reduction r The manufacturer decides the unit selling price of the new product p_m The remanufacturer further determines the unit selling price of the remanufactured product based on the manufacturer's decision. p_r The manufacturer decides on the level of carbon reduction in the supply chain. The dominant player predicts the response of the follower to its own decision based on empirical information, and prioritizes its decision in order to obtain the maximum benefit; the follower determines its own optimal decision after the dominant player has made a decision, so the Stackelberg model is constructed for the master-slave game.

2.2. Relevant Assumptions

The following assumptions are made in this paper in order to facilitate the solution of the model and to ensure the rationality of the model:

Hypothesis 1: Assuming that there is no difference between new and remanufactured products in terms of appearance and performance, consumers' willingness to pay for new and remanufactured products is$v$, thebv , with reference to Liu Huaishang et al. (2023) [1] 's study, the random variable v obeys the (0, α) of the uniform distribution. b denotes the consumer price sensitivity coefficient and $\frac{p_m}{p_r} < b < 1$. The utility functions of consumers for purchasing new and remanufactured products are respectively:

$$U_1 = v - p_m \tag{1}$$

$$U_2 = v - p_r \tag{2}$$

When $U_1 > U_2$ time, consumers will choose to buy new products, and when $0 < U_1 < U_2$ when consumers will choose to buy the remanufactured product, the demand for the new product is $\alpha - \frac{p_m - p_r}{1-b}$ and the demand for the remanufactured product is $\frac{bp_m - p_r}{1-b}$ The demand for new products is, and the demand for remanufactured products is. Consumers' purchasing desire will increase with the greenness of the product, and the sensitivity coefficient of market demand to greenness is k. After considering the greenness of the product, the new market demand function for consumers to choose to buy the new product is

$$D_1 = \alpha - \frac{p_m - p_r}{1-b} + kg \tag{3}$$

$$D_2 = \frac{bp_m - p_r}{1-b} + kg \tag{4}$$

Assumption 2: g Is the greenness of the product and $g \geq 0$, the level of product greenness determines how friendly the product is to the environment. The level of product greenness can be reflected by some indicators, such as green certification, energy efficiency rating, carbon labeling, life cycle assessment report, energy efficiency labeling, recyclability and packaging reduction, and third-party environmental certification.

Assumption 3: Manufacturers need to consider the greenness of their products by increasing investment in R & D and improving the level of technology, R & D results and R & D investment are in a quadratic relationship, so the cost of developing green products is $\frac{1}{2}\eta g^2$ The cost of R & D of green products is η is the investment coefficient of the manufacturer for green products.

2.3. Model Symbols

Table 1. lists the symbols covered in the text

Symbol	Meaning
v	Consumer willingness to buy new products
b	Price sensitivity coefficient of product demand
r	Carbon reduction levels of manufacturers
h	Emission reduction factor per unit of new product brought by a manufacturer's green investment
a	market size
p_m, p_r	Price per unit of product for new/remanufactured products
p_c	Price per unit of carbon emissions traded
g	Greenness per unit of product
k	Sensitivity factor of market demand to greenness
η	Coefficient of investment in green products by manufacturers
c_m, c_r	Unit production cost of new/remanufactured products
e_m	Total carbon emissions from the production of new products
e	Carbon emissions per unit of new product

3. Model Solving

Under decentralized decision making, the supply chain members aim to maximize their own interests, when the profit functions of the manufacturer and remanufacturer are respectively:

$$\Pi_1 = D_1(p_m - c_m) + p_c(e_m - (e - hr)D_1) - \frac{1}{2}\eta g^2 \quad (5)$$

$$\Pi_2 = D_2(p_r - c_r) \quad (6)$$

In this paper, the model is solved using the inverse solution method. Taking first order as well as second order derivatives of the profit function of the remanufacturer, we have $\frac{\partial^2 \Pi_2}{\partial p_r^2} = -\frac{2}{1-b} < 0$ Therefore, it can be shown that $\frac{\partial \Pi_2}{\partial p_r} = 0$ The optimal price can be obtained p_r^* so that the profit of the remanufacturer is maximized. $p_r^* = \frac{1}{2}(bp_m - kgb + kg + c_r)$. According to the inverse induction method, it is substituted into the manufacturer's profit function Π_1 in the manufacturer's profit function, and then separately on the manufacturer's profit function Π_1 Find the price of the new product p_m and product greenness g the first-order and second-order partial derivatives and the corresponding determinant of the Hessian matrix, which can be obtained as $\frac{4(2-b)(-\eta)-9k^2(b-1)}{4b-4} < 0$ i.e. $\eta > \frac{9(b-1)}{4(b-2)}k^2$ At this time, the Hessian matrix is negatively determined and is a concave function. At this time there exists p_m^*, g^* optimal solution that maximizes the manufacturer's profit.

$$p_m^* = \frac{\left(\left((2hr-2e)p_c-4\alpha-2c_m\right)b+(4e-4hr)p_c+4\alpha+4c_m+2c_r\right)\eta+9\left((e-hr)p_c+c_m\right)k^2(b-1)}{(-4b+8)\eta+9k^2(b-1)} \quad (7)$$

$$g^* = \frac{3k\left(\left((-hr-e)p_c-2\alpha+c_m\right)b+(2hr-e)p_c+2\alpha-2c_m+c_r\right)}{(9k^2-4\eta)b-9k^2+8\eta} \quad (8)$$

Order $\frac{\partial \Pi_1}{\partial p_m} = 0$, $\frac{\partial \Pi_1}{\partial g} = 0$, the optimal solution for the remanufacturer can be obtained by substituting p_m^*, g^* the optimal solution of the remanufacturer, substituted into the optimal response function of the remanufacturer p_r and the manufacturer and remanufacturer profit function equation, can obtain the manufacturer and remanufacturer's respective profits.

$$\Pi_1 = \frac{((-(-hr-e)^2(b-2)^2p_c^2-8(b-2)(((\left(-\frac{hr}{4}+\frac{e}{4}\right)c_m+\left(\frac{hr}{2}-\frac{e}{2}\right)\alpha+e_m)b+\left(\frac{hr}{2}-\frac{e}{2}\right)c_m+\left(-\frac{hr}{2}+\frac{e}{2}\right)\alpha-\frac{c_r hr}{4}+\frac{c_r e}{4}-e_m)p_c-4\left(\left(\alpha-\frac{c_m}{2}\right)b-\alpha+c_m-\frac{c_r}{2}\right)^2)\eta+18e_m p_c k^2(b-1)^2)}{-8(b-2)(b-1)\eta+18k^2(-1+b)^2} \quad (9)$$

$$\Pi_2 = -\frac{(9((((-hr-e)p_c+\alpha+c_m)k^2-\frac{\eta((-hr+e)p_c+2\alpha+c_m)}{3})b^2+\left((-2c_r-2\alpha)k^2+\frac{2\left((-hr+e)p_c+\alpha+c_m+\frac{3c_r}{2}\right)\eta}{3}\right)b+((hr-e)p_c+2c_r+\alpha-c_m)k^2-\frac{4\eta c_r}{3})^2)}{(9bk^2-4\eta b-9k^2+8\eta)^2(b-1)} \quad (10)$$

4. Decision Analysis

This paper investigates the relationship between the carbon emission reduction coefficient, the carbon emission reduction level, the sensitivity coefficient of market demand to greenness, the investment coefficient of green technology, the relationship between the carbon trading price and the greenness of the product, the price of new and remanufactured products, and the profit of the remanufacturing supply chain members, respectively, as a result of the manufacturer's green investment.

Corollary 1 Under $\eta > \frac{9(b-1)}{4(b-2)}k^2$, the optimal prices of new and remanufactured products are positively correlated with the emission reduction coefficients per unit of new product brought about by the manufacturer's green investment, as shown in Table 1 below. h is positively correlated, indicating that the emission reduction coefficient from the manufacturer's green investment contributes to higher product prices.

Prove: the optimal price for a new product and a remanufactured product p_m^*, p_r^* find the first-order derivative of the coefficient of emission reduction per unit of new product brought by the manufacturer's green investment h The first-order derivative of the coefficient of emission reduction per unit of new product due to $\eta > \frac{9(b-1)}{4(b-2)}k^2$. $1 < b < 1$.

$$\frac{\partial p_m^*}{\partial h} = \frac{(2bp_c-4rp_c)\eta-9rp_ck^2(-1+b)}{(-4b+8)\eta+9k^2(-1+b)} > 0 \quad (11)$$

$$\frac{\partial p_r^*}{\partial h} = -\frac{rp_c(3b^2k^2-b^2\eta+2b\eta-3k^2)}{(-4b+8)\eta+9k^2(-1+b)} > 0 \quad (12)$$

Corollary 2 Under $\eta > \frac{9(b-1)}{4(b-2)}k^2$ Under the condition that when $h > \frac{e}{r} + \frac{c_m}{p_c r} + \frac{-c_r - 2\alpha(1-b)}{p_c(2-b)r}$ when there are $\frac{\partial p_m{}^*}{\partial k} > 0$, the $\frac{\partial p_r{}^*}{\partial k} > 0$, $\frac{\partial \Pi_1{}^*}{\partial k} > 0$, $\frac{\partial \Pi_2{}^*}{\partial k} > 0$ and $\frac{\partial g^*}{\partial k} > 0$.

Proof: using the optimal prices of new and remanufactured products $p_m{}^*$, $p_r{}^*$, the optimal profit function of the manufacturer and remanufacturer $\Pi_1{}^*, \Pi_2{}^*$ and the optimal greenness of the product g^* find the first order derivative with respect to the sensitivity coefficient k of the market demand to the greenness, since $\eta > \frac{9(b-1)}{4(b-2)}k^2$, $h > \frac{e}{r} + \frac{c_m}{p_c r} + \frac{-c_r - 2\alpha(1-b)}{p_c(2-b)r}$.

$$\frac{\partial p_m{}^*}{\partial k} = -\frac{36k(-1+b)(((-hr+e)p_c-2\alpha+c_m)b+(2hr-2e)p_c+2\alpha-2c_m+c_r)\eta}{(9bk^2-4b\eta-9k^2+8\eta)^2} > 0 \qquad (13)$$

$$\frac{\partial p_r{}^*}{\partial k} = -\frac{6k(-1+b)(b+4)(((-hr+e)p_c-2\alpha+c_m)b+(2hr-2e)p_c+2\alpha-2c_m+c_r)\eta}{(9bk^2-4b\eta-9k^2+8\eta)^2} > 0 \qquad (14)$$

$$\frac{\partial \Pi_1{}^*}{\partial k} = \frac{\frac{\left(((-hr+e)p_c-2\alpha+c_m)b+(2hr-2e)p_c+2\alpha-2c_m+c_r\right)^2}{9k\eta}}{(9bk^2-4b\eta-9k^2+8\eta)^2} > 0 \qquad (15)$$

$$\frac{\partial \Pi_2{}^*}{\partial k} = \frac{\left(\left(\left(((-hr+e)p_c+\alpha+c_m)k^2-\frac{\eta((-hr+e)p_c+2\alpha+c_m)}{3}\right)b^2 + \left((-2\alpha-2c_r)k^2+\frac{2\left((-hr+e)p_c+\alpha+c_m+\frac{3}{2}c_r\right)\eta}{3}\right)b + ((hr-e)p_c+\alpha-c_m+2c_r)k^2-\frac{4\eta c_r}{3}\right)36k(b+4)\eta\,(((-hr+e)p_c-2\alpha+c_m)b+(2hr-2e)p_c+2\alpha-2c_m+c_r))}{(9bk^2-4b\eta-9k^2+8\eta)^3} > 0 \qquad (16)$$

$$\frac{\partial g^*}{\partial k} = -\frac{27\left(\left(k^2+\frac{4\eta}{9}\right)b-k^2-\frac{8\eta}{9}\right)\left(((-hr+e)p_c-2\alpha+c_m)b+(2hr-2e)p_c+2\alpha-2c_m+c_r\right)}{(9bk^2-4b\eta-9k^2+8\eta)^2} > 0 \qquad (17)$$

Corollary 2 shows that when the carbon reduction level of the manufacturer reaches a certain level ($h > \frac{e}{r} + \frac{c_m}{p_c r} + \frac{-c_r - 2\alpha(1-b)}{p_c(2-b)r}$), the greater the sensitivity coefficient of market demand to greenness, the demand for green products is further enhanced, the optimal price of new and remanufactured products increases, the profit of remanufacturers increases, and the greenness of products also increases. And the profit of the manufacturer regardless of the carbon emission reduction level of the $h > \frac{e}{r} + \frac{c_m}{p_c r} + \frac{-c_r - 2\alpha(1-b)}{p_c(2-b)r}$ The greater the sensitivity factor of market demand to greenness, the higher the manufacturer's profit.

Corollary 3 Under $\eta > \frac{9(b-1)}{4(b-2)}k^2$ under which there are $\frac{\partial p_m{}^*}{\partial r} > 0$, $\frac{\partial p_r{}^*}{\partial r} > 0$, $\frac{\partial \Pi_1{}^*}{\partial r} > 0$, $\frac{\partial \Pi_2{}^*}{\partial r} > 0$, $\frac{\partial g^*}{\partial r} > 0$. The level of carbon emission reduction positively contributes to each decision variable as well as to the profits of supply chain members.

The proof of Corollary 3 is similar to Corollary 2 and will not be repeated here. From the derivation results, it can be seen that the stronger the level of carbon emission reduction, the more conducive to the enhancement of product greenness, which also further increases the market demand for green products. The sales price of new and remanufactured products will also increase, which will effectively increase the profit margins of manufacturers and retailers along with the potential market demand and price increase.

Corollary 4 Under $\eta > \frac{9(b-1)}{4(b-2)}k^2$, the optimal greenness under g^* decreases as the green investment coefficient η decreases with the increase of the optimal profit of the manufacture $\Pi_1{}^*$ decreases as the green investment coefficient η decreases with the increase of the green investment coefficient. The optimal price of new and remanufactured products $p_m{}^*$, $p_r{}^*$ The optimal price of new products and remanufactured products, when the manufacturer's carbon emission reduction level reaches a certain level (i.e. $h > \frac{e}{r} + \frac{c_m}{p_c r} + \frac{-c_r - 2\alpha(1-b)}{p_c(2-b)r}$ when the manufacturer's carbon reduction level reaches a certain level (i.e.)) decreases with the increase of the green investment factor η decreases as the green investment coefficient increases.

Proof: using the optimal greenness g^* , the optimal profit of the manufacturer $\Pi_1{}^*$ and the optimal prices of new and remanufactured products $p_m{}^*, p_r{}^*$ Find the first-order derivative with respect to the green investment coefficient η The first order derivative of the green investment coefficient due to $\eta > \frac{9(b-1)}{4(b-2)}k^2$ the

$$\frac{\partial p_m{}^*}{\partial \eta} = \frac{18k^2(((-hr+e)p_c-2\alpha+c_m)b+(2hr-2e)p_c+2\alpha-2c_m+c_r)(-1+b)}{(9bk^2-4b\eta-9k^2+8\eta)^2} \qquad (18)$$

$$\frac{\partial p_r{}^*}{\partial \eta} = \frac{3k^2(-b+1)(b+4)((-hr+e)p_c-2\alpha+c_m)b+(2hr-2e)p_c+2\alpha-2c_m+c_r}{(9bk^2-4b\eta-9k^2+8\eta)^2} \qquad (19)$$

When $h > \frac{e}{r} + \frac{c_m}{p_c r} + \frac{-c_r - 2\alpha(1-b)}{p_c(2-b)r}$, $\frac{\partial p_m{}^*}{\partial \eta} < 0$, $\frac{\partial p_r{}^*}{\partial \eta} < 0$ when $h > \frac{e}{r} + \frac{c_m}{p_c r} + \frac{-c_r - 2\alpha(1-b)}{p_c(2-b)r}$, $\frac{\partial p_m{}^*}{\partial \eta} > 0$, $\frac{\partial p_r{}^*}{\partial \eta} > 0$.

$$\frac{\partial \Pi_1{}^*}{\partial \eta} = -\frac{(((-hr+e)p_c-2\alpha+c_m)b+(2hr-2e)p_c+2\alpha-2c_m+c_r)^2 * 9k^2}{2(9bk^2-4b\eta-9k^2+8\eta)^2} < 0 \qquad (20)$$

$$\frac{\partial g^*}{\partial \eta} = -\frac{3k\left(((-hr+e)p_c-2\alpha+c_m)b+(2hr-2e)p_c+2\alpha-2c_m+c_r\right)}{\left((9k^2-4\eta)b-9k^2+8\eta\right)^2} < 0 \qquad (21)$$

Corollary 4 shows that the price of new and remanufactured products decreases with the increase of the green technology investment coefficient when certain conditions are met. η increases, which means that the green technology investment coefficient η This means that the green technology investment coefficient can induce manufacturers to reduce the price of new and remanufactured products under certain conditions, and at the same time, the increase of the green technology investment coefficient η This means that the green technology investment coefficient can induce manufacturers to reduce the price of new and remanufactured products under certain conditions, while the increase of the green technology investment coefficient reduces the greenness of the products and decreases the profit of manufacturers.

Corollary 5 Under $\eta > \frac{9(b-1)}{4(b-2)}k^2$ Under, when the carbon reduction level of the manufacturer reaches a certain level (i.e., the $h > \frac{e}{r} + \frac{c_m}{p_c r} + \frac{-c_r - 2\alpha(1-b)}{p_c(2-b)r}$ when), the optimal greenness g^* , the optimal price of remanufactured products p_r^* decreases as the carbon trading price p_c decreases with the increase of carbon trading price, and the optimal price of new product p_m^* increases as the carbon trading price p_c increases.

Proof: with optimal greenness g^*, the optimal price of new and remanufactured products p_m^*, p_r^* Find the first-order derivative with respect to the price of carbon trading, since $\eta > \frac{9(b-1)}{4(b-2)}k^2$ when $h > \frac{e}{r} + \frac{c_m}{p_c r} + \frac{-c_r-2\alpha(1-b)}{p_c(2-b)r}$

$$\frac{\partial p_m^*}{\partial p_c} = \frac{((2hr-2e)b-4hr+4e)\eta+9(-hr+e)k^2(-1+b)}{(-4b+8)\eta+9k^2(-1+b)} > 0 \quad (22)$$

$$\frac{\partial p_r^*}{\partial p_c} = \frac{(3b^2k^2-b^2\eta+2b\eta-3k^2)(-hr+e)}{(-4b+8)\eta+9k^2(-1+b)} < 0 \quad (23)$$

$$\frac{\partial g^*}{\partial p_c} = \frac{3k((-hr+e)b+2hr-2e)}{(9k^2-4\eta)b-9k^2+8\eta} < 0 \quad (24)$$

Corollary 5 shows that when certain conditions are met, the price of remanufactured products decreases as the carbon trading price p_c increases, while the price of new products increases, which means that the carbon trading price has a significant effect on the optimal price of new products and remanufactured products. the government can macro-control the price of products through the carbon trading price, while the carbon trading price p_c will decrease the greenness of products.

5. Numerical Analysis

This paper examines the reasonableness of the model conclusions through numerical analysis, focusing on the impact of the green preference coefficient on each decision variable. The values of the model parameters are: $a = 200$, $b = 0.8$, $c_m = 50$, $c_r = 25$, $\eta = 0.85$, $e = 10$, $e_m = 100$, $p_c = 1$, $r = 5$, $k = 1.2$.

From Figure 1 it can be seen that the price of new and remanufactured products increases as the emission reduction coefficient from the manufacturer's green investment increases, indicating that the emission reduction coefficient from the manufacturer's green investment helps to increase the price of the product.

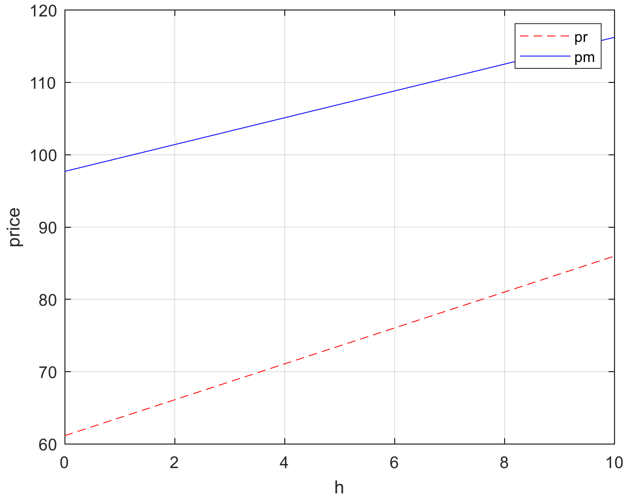

Figure 1. The abatement factor resulting from manufacturers' green investments on the optimal price

It is demonstrated by Fig. 2, Fig. 3, Fig. 4 that when $k \in (0, 1)$ different and the other parameters are constant, the value of h is fixed at 0.5, Satisfaction $h > \frac{e}{r} + \frac{c_m}{p_c r} + \frac{-c_r-2\alpha(1-b)}{p_c(2-b)r}$ of the new and remanufactured product prices, manufacturer and remanufacturer profits and greenness. From Fig. 2, Fig. 3, Fig. 4, it can be found that the sensitivity coefficient of market demand to greenness k has a positive effect on the price of new and remanufactured products, the profit of manufacturers and remanufacturers, and the degree of greenness. In addition, Corollary 3 involves that the effect of carbon emission reduction level on decision variables and objective function is similar to the effect of market demand on the sensitivity coefficient of greenness, so it is not shown graphically.

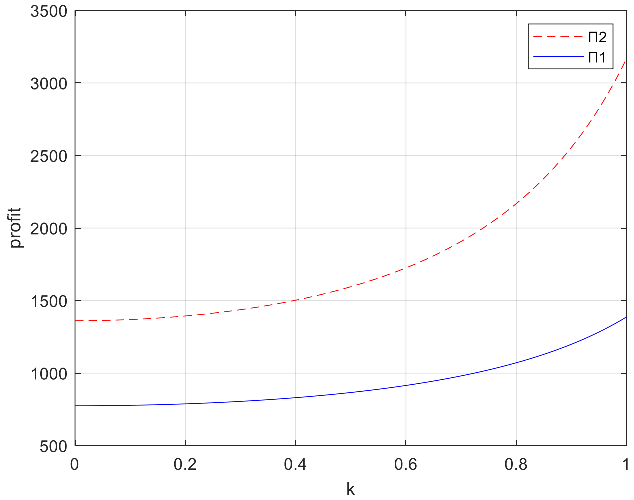

Figure 2. The influence of sensitivity coefficient k of market demand to greenness on optimal profit

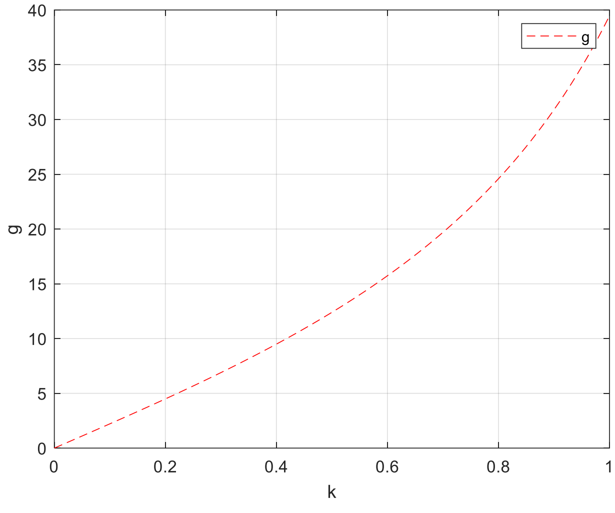

Figure 3. The influence of market demand sensitivity coefficient k on greenness

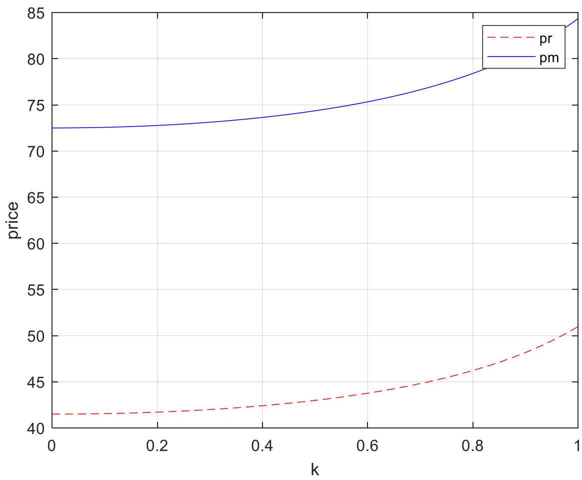

Figure 4. The influence of sensitivity coefficient k of market demand to greenness on the optimal price

It is demonstrated by Fig. 5, Fig. 6, Fig. 7 that when $\eta \in (0.85, 1)$ different and other parameters are constant, the$h$ value is fixed at 0.5, the price of new and remanufactured products, the profit of manufacturer and remanufacturer and the change of green degree. From Fig. 5, Fig. 6, Fig. 7, it can be found that under certain conditions, the green technology investment coefficient has a negative impact on the price of new and remanufactured products, manufacturer's profit, and green degree.

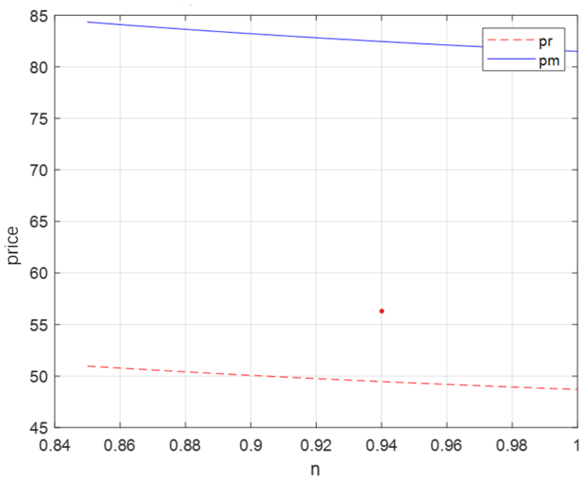

Figure 5. The effect of green technology investment coefficient η on the optimal price

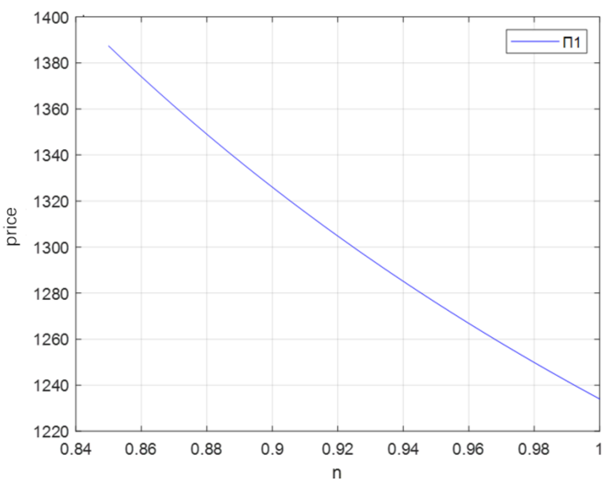

Figure 6. The effect of green technology investment coefficient η on manufacturers' profits

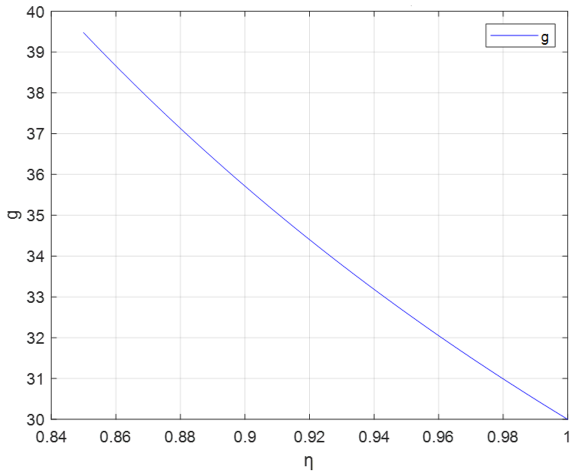

Figure 7. The influence of green technology investment coefficient η on greenness

It is demonstrated by Fig. 8, Fig. 9 that when $p_c \in (0, 3)$ different and other parameters are constant, the h, k The value is fixed to 1, the change of the price of new and remanufactured products, the profit of manufacturer and remanufacturer and the green degree. From Fig. 8, Fig. 9, it can be found that under certain conditions, the carbon trading price has a positive effect on the price of new products and a negative effect on the price and greenness of remanufactured products.

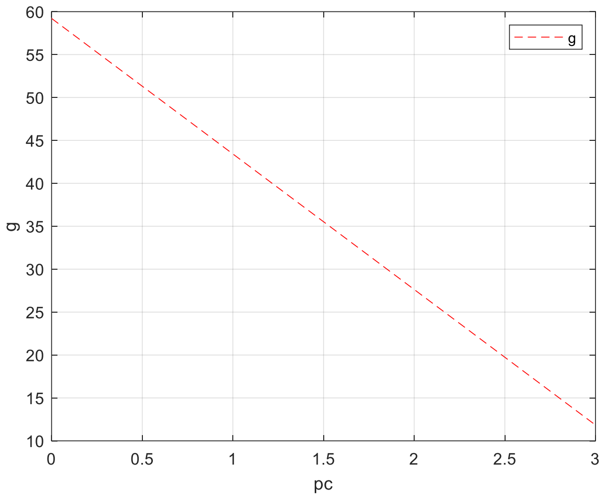

Figure 8. The influence of carbon trading price on greenness

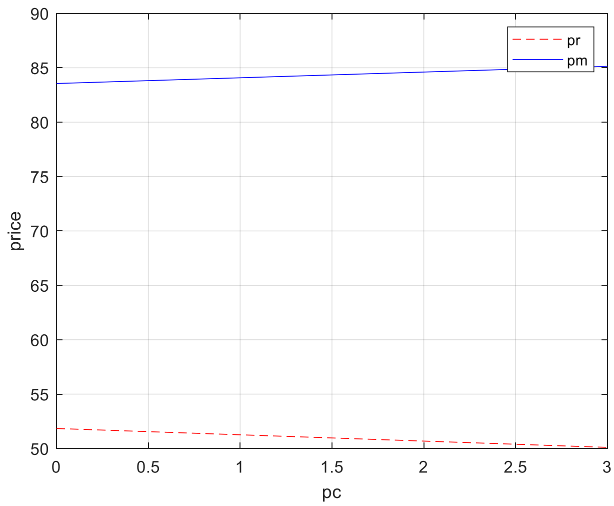

Figure 9. The effect of carbon trading price on the optimal price

6. Conclusion

This paper constructs a model of remanufacturing supply chain formed by manufacturer, third party manufacturer under carbon trading policy. The effects of carbon emission reduction level, market demand sensitivity coefficient to greenness, and green technology investment coefficient on the decision-making of pricing and profit of the whole remanufacturing supply chain are explored. The results of the study show that (1) when manufacturers actively invest in greenness, thus increasing the corresponding carbon emission reduction coefficients, they are able to drive the prices of new and remanufactured products. (2) Consumers' green preference behavior can expand the market demand for green products, i.e., it is manifested in the increase of market demand sensitivity coefficient to greenness, and at the same time, the manufacturer should also simultaneously invest more costs in carbon emission reduction level to make it reach a certain level, and at this time, the manufacturer and the remanufacturer also get the price and the profit enhancement. (3) Manufacturers with the increase of green investment coefficient, green technology investment costs are getting bigger and bigger, resulting in shrinking profit margins and decreasing greenness, and the prices of new and remanufactured products are also decreasing when the level of carbon emission reduction reaches a certain level. (4) The increase of carbon trading price will lead to the decrease of greenness; the price of new products will increase and the price of remanufactured products will decrease.

In summary, the following management insights can be obtained: (1) members of the remanufacturing supply chain should set up a clear carbon emission reduction target, while deepening the low-carbon green aspects, which is conducive to the development of the remanufacturing supply chain; (2) in the process of the development of the remanufacturing supply chain, the government can reasonably control the price of the carbon trading market, to keep the market price tends to be stable, so that the price of the carbon traded is in a suitable range, which is conducive to the promotion of the remanufacturing supply chain in the development of low-carbon green road (3) The development of remanufacturing supply chain can further increase the green concept of consumers, deeply rooted in the concept of green consumption, and reduce the cost of green technology investment in order to obtain higher profits.

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