Research Article

Influence of Government Subsidy on Remanufacturing Decision under Different Market Models

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This paper considers a remanufacturing closed-loop supply chain involving a manufacturer and an independent remanufacturer. First, it analyzes the decision-making changes under three market leadership (manufacturer leadership, remanufacturer leadership, and no leadership) models before and after government subsidies. Considering the government's goal of maximizing social welfare, the study establishes a two-stage game model for the government's optimal price subsidy. It also considers the effects of consumer environmental preferences on product prices, demand, profits, government subsidies, and social welfare under different market models. The study found that government subsidy effectively stimulates the demand for remanufactured products, reduces the price of both new and remanufactured products, and promotes the remanufacturing industry. Furthermore, improvement in consumer environmental awareness was found to enhance the government's optimal subsidy.

1. Introduction

As environmental problems continue to worsen, many companies have turned to remanufacturing activities. Remanufacturing is the process of recycling, processing, and equating used products with new products in the independent market [1]. Remanufacturing activities have actively responded to the call for sustainable development advocated by China to promote a circular economy. Product remanufacturing plays a very important role in the circular economy [2].

The Chinese remanufacturing industry is currently in its infancy. Because of capital and technology constraints in the Chinese market, most local companies have encountered a series of problems related to production and sales of remanufactured products, such as high remanufacturing costs and unwillingness of consumers to pay for remanufactured products, etc., always placing rework products at a competitive disadvantage in the market. The governments in Europe, the United States, and Japan have used financial tools to enhance the remanufacturing industry [3]. In order to promote the remanufacturing industry, the Chinese government issued the "Remanufacturing Products 'Replacing old products with new ones' Pilot Implementation Plan" in 2013, officially

proposing government subsidies for the promotion of remanufactured products. Government subsidies are considered the most direct way to rapidly promote the Chinese remanufacturing industry. The Chinese government has played an important role in promoting product consumption and economic growth during the initial stages.

In the remanufacturing industry, it is very common for manufacturers to take responsibility for recycling and remanufacturing products. For example, Hewlett-Packard, Kodak, and IBM have been recycling and remanufacturing old products since the last century. When the distance between the production and sales centers is large, manufacturers may have the advantage of technology and brand, but may not take up the recycling of old products because of higher transportation and inventory costs, thus prompting the emergence of third-party remanufacturers. In China, a company represented by Wuhan Maxima Engineering Machinery Remanufacturing Co., Ltd., has specialized in third-party remanufacturing, to form a certain scale. The emergence of third-party remanufacturing companies has added more participants to the supply chain. Thus, the original manufacturer has to face two markets, that is, for new products and remanufactured products; moreover, the two markets influence each other,

making the market competition more complex and market decision-making more complicated.

Exploring the competitive relationship between the manufacturers and remanufacturers under different market leadership models can provide a theoretical basis for corporate decision-making. Some scholars have paid attention to the effect of government subsidies on remanufacturing under different market structures. Zhao et al. constructed a decision-making model for remanufacturers and consumers, considering the environmental preferences of consumers and the impact of government subsidies, to find that when remanufacturers and consumers share a certain percentage of subsidies, both make more profits [4]. Xiao et al. explored a single-cycle model from a single manufacturer to a single remanufacturer, considering three government subsidies, to find that government subsidies always play a positive role in the remanufacturing industry and find the best subsidy choice for remanufacturers [5]. Zhu et al. constructed a two-stage game model for the government and manufacturer, to compare subsidy donation and subsidy transfer. They show that subsidy donation can increase the total demand of products relative to subsidized sales [6]. Zhen et al. stipulated that the supply chain participants should include new product manufacturers, recyclers, and remanufacturers and analyzed the changes in game decision-making with new product manufacturers as leaders under the three scenarios including no government subsidies, only government subsidies, and both government subsidies and taxes. They proposed that government subsidies and taxation have asymmetric effects [7]. Hai-mi et al. proposed a two-stage closed-loop supply chain model consisting of manufacturers and retailers, considering the government's participation in a game model with manufacturers as market leaders, and analyzing the impact of different government subsidy policies on the decision-making of supply chain participants. They found that the combination of various subsidy policies can better improve the overall profit and operation effect of the supply chain [8]. Chemama et al. simulated the interaction between government and supply chain participants in a case of uncertain demand, to find the impact of decision time, and providing a basis for the formulation of government subsidy programs [9]. Zhao et al. designed a two-stage game model for manufacturers, remanufacturers, and retailers, to analyze the decision-making changes of manufacturers and remanufacturers in three scenarios related to government subsidies. The results showed that government subsidies for remanufacturers can increase the market competitiveness of remanufacturers, while government subsidies for consumers can have a major impact on the remanufactured products' market competitiveness [10]. Wan et al. built a dual-channel recycling of used products model with manufacturers as market leaders and analyzed the policy effects of government subsidies and other policies on the closed-loop supply chain, to find that remanufacturing subsidies stimulate consumption and increase the profitability of the supply chain members [11]. Sun et al. studied the government subsidies for remanufacturers, with the remanufacturers as suppliers and competitors, to demonstrate that government subsidies have a major impact on the remanufacturers' model choices [12].

Considering the effects of government subsidies on remanufacturing competition, the above studies generally focus on a market-leading model, such as manufacturers or remanufacturers in market leadership positions. As some remanufacturers continue to grow, they have demonstrated their ability to lead the remanufacturing in the supply chain. For example, Caterpillar, the world's leading remanufacturer, has gradually become the chief supplier of Land Rover, remanufacturing products in its supply chain strategic partnership, and becoming a core company and leader in supply chain cooperation. This clearly indicates that many market structures are formed by manufacturers and remanufacturers, including manufacturers as market leaders (*ML*), remanufacturers as market leaders (*RL*), and no-market leaders (*NL*). The difference in market leadership patterns directly affects the game order of both parties to the competition, and this in turn affects the decision-making and competition of members in the supply chain. Therefore, government subsidies play an important role in the impact of manufacturers and remanufacturers on different market models.

This study examines the real background of significant differences in consumer willingness to pay, to first construct two different market scenarios, namely, with government subsidies, and without government subsidies, and then propose three market leadership models, *ML*, *RL*, and *NL* models. It then discusses the impact of two market scenarios, that is, with and without government subsidies, on the competition decision between manufacturers and remanufacturers under different market leadership models; studies how the government should formulate optimal subsidies under the corresponding scenarios; and provides a theoretical basis for promoting the remanufacturing industry.

This paper presents the following innovations. (1) It considers three types of market leadership structures existing in remanufacturing competition. (2) It analyzes the change in decision parameters of each remanufacturing supply chain member under the three market structures as well as the two scenarios of with and without government subsidies. (3) It considers the impact of consumer environmental preferences on the members' profits, government subsidies, and social welfare in the remanufacturing supply chain. The three innovation points render the study more systematic and realistic.

2. Problem Description and Model Construction

This paper considers a remanufacturing supply chain involving a single manufacturer and a single independent remanufacturer. While the manufacturer is responsible for production and sale of new products, the remanufacturer is responsible for production and sale of remanufactured products as an independent manufacturer. This paper examines two market scenarios, that is, without government subsidies and with government subsidies, as shown in Figure 1. The two market scenarios consider the *ML*, *RL*, and *NL* market leadership models.

TABLE 1: The related variables and parameter comments.

Variable	Parameter comment
p_n, p_r	Indicating the sales price of new products and reworks
q_n, q_r	Indicating the demand for new products and remanufactured products
c_n, c_r	Indicating the manufacturing costs of new products and remanufactured products
π_n, π_r	Indicating the profit of new products and remanufactured products
cs_n, cs_r	Indicating the total consumer surplus of consumers purchasing new products for remanufactured products. That is, the consumer's willingness to pay for the product minus the actual price paid for purchase of the product.
s	Indicating the unit price subsidy granted by the government for remanufactured products. Government subsidy costs cannot be unlimited, regulating $s \geq 0$.
Q_0	Indicating the market size; the market size assumptions in this article are unchanged
θ	Indicating the consumer's preference coefficient. That is, the consumer's willingness to pay for the remanufactured products is θ times the willingness to pay for the new product.
v	Indicating consumer willingness to pay for new products

FIGURE 1: The market structure diagram with and without government subsidies.

2.1. Symbol Convention. Superscript i in the text indicates the manufacturer leadership model (denoted as M), remanufacturer leadership model (denoted as R), and no leadership model (denoted as N); subscript j represents the manufacturer-related variables (denoted as n) and remanufacturer-related variables (denoted as r); the symbol $*$ indicates an equilibrium solution or an optimal solution. The relevant variables and parameters are shown in Table 1.

2.2. Demand Function and Consumer Surplus

2.2.1. Demand Function. This article assumes that although reworks and new products are basically the same in quality, function, and shape, consumers can effectively identify the two and have different preferences. Both the manufacturer and remanufacturer are assumed to use order-to-order production, such that the demand is equal to the sales volume with no inventory. Assume that the market size is r and the consumers' willingness to pay for new products is v . From the literature [13], Q_0 indicates the consumer's highest willingness to pay for new products, and v is uniformly distributed $[0, 1]$, its cumulative distribution function assumed to be $F(v) = v/Q_0$. Consumers generally are less willingness to pay for reworks than for new products. Assuming that the consumers' willingness to pay for reworks is a θ multiple of the willingness to pay for new products (θ is the consumer's preference coefficient), and $\theta \in [0, 1]$, the larger θ , the greater is the consumer desire for reworks; that is, the stronger the

environmental awareness of consumers. If the consumers' willingness to pay for remanufactured products is θv , when $p_n - (1 - \theta)Q_0 < p_r < \theta p_n$, the consumers have demand for both new products and reworks. The demand function is

$$q_n = Q_0 \int_{(p_n - p_r)/(1 - \theta)}^{Q_0} dF(v) = Q_0 - \frac{p_n - p_r}{1 - \theta} \quad (1)$$

$$q_r = Q_0 \int_{p_r/\theta}^{(p_n - p_r)/(1 - \theta)} dF(v) = \frac{\theta p_n - p_r}{\theta(1 - \theta)} \quad (2)$$

2.2.2. Consumer Surplus. In this paper, cs_n and cs_r represent, respectively, the total consumer surplus for purchasing new products and reworks. From the above analysis of the demand function, consumers demand new products only when they are willing to pay for new products $v \in [(p_n - p_r)/(1 - \theta), Q_0]$. Since v is uniformly distributed, the total consumer surplus for purchasing new products at that time can be expressed as

$$\begin{aligned} CS_n &= \int_0^{q_n} v dv - p_n q_n \\ &= \left[\frac{Q_0 + (p_n - p_r)/(1 - \theta)}{2} - p_n \right] q_n \end{aligned} \quad (3)$$

Similarly, when the consumers' willingness to pay is $v \in [p_r/\theta, (p_n - p_r)/(1 - \theta)]$, that is, $\theta v \in [p_r, \theta(p_n - p_r)/(1 - \theta)]$, consumers will have demand for reworks. Since

θv is uniformly distributed, the total consumer surplus for purchasing remanufactured products at that time can be expressed as

$$\begin{aligned} CS_r &= \int_0^{q_r} \theta v d(\theta v) - p_r q_r \\ &= \left[\frac{\theta(p_n - p_r) / (1 - \theta) + p_r}{2} - p_r \right] q_r \end{aligned} \quad (4)$$

3. Model Analysis

3.1. Anarchy Subsidy Scenario

3.1.1. Manufacturer Is the Market Leader (ML Model)

Phase 1. The manufacturer determines the price of new products (p_n^M).

Phase 2. Remanufacturers set the optimal reworks' prices to maximize their profits considering the consumer demand for new products and reworks in the market.

The profit function of both parties is

$$\max_{p_r} \pi_r^M = (p_r^M - c_r^M) \left(\frac{\theta p_n^M - p_r^M}{\theta(1 - \theta)} \right) \quad (5)$$

$$\max_{p_n} \pi_n^M (p_n^M | p_r^M) = (p_n^M - c_n^M) \left(Q_0 - \frac{p_n^M - p_r^M}{1 - \theta} \right) \quad (6)$$

Using the idea of reverse solution, the price and demand of new products and reworks under the manufacturer's leadership model and the profits of manufacturers and remanufacturers are obtained, respectively, as follows:

$$\begin{aligned} p_n^{M*} &= \frac{2(1 - \theta)Q_0 + (2 - \theta)c_n + c_r}{2(2 - \theta)} \\ p_r^{M*} &= \frac{2\theta(1 - \theta)Q_0 + \theta(2 - \theta)c_n + (4 - \theta)c_r}{4(2 - \theta)} \\ q_n^{M*} &= \frac{2(1 - \theta)Q_0 - (2 - \theta)c_n + c_r}{4(1 - \theta)} \\ q_r^{M*} &= \frac{2\theta(1 - \theta)Q_0 + \theta(2 - \theta)c_n - (4 - 3\theta)c_r}{4\theta(1 - \theta)(2 - \theta)} \\ \pi_n^{M*} &= \frac{[2(1 - \theta)Q_0 - (2 - \theta)c_n + c_r]^2}{8(1 - \theta)(2 - \theta)} \\ \pi_r^{M*} &= \frac{[2\theta(1 - \theta)Q_0 + \theta(2 - \theta)c_n - (4 - 3\theta)c_r]^2}{16\theta(1 - \theta)(2 - \theta)^2} \end{aligned} \quad (7)$$

3.1.2. Remanufacturer Is the Market Leader (RL Model)

Phase 1. The remanufacturer determines the price of the remanufactured product (p_r^R).

Phase 2. Manufacturers set the optimal price of new products to maximize their profits considering the consumer demand for new products and reworks in the market.

The profit function of both parties is as follows:

$$\max_{p_n} \pi_n^R = (p_n^R - c_n^R) \left(Q_0 - \frac{p_n^R - p_r^R}{1 - \theta} \right) \quad (8)$$

$$\max_{p_r} \pi_r^R (p_r^R | p_n^R) = (p_r^R - c_r^R) \left(\frac{\theta p_n^R - p_r^R}{\theta(1 - \theta)} \right) \quad (9)$$

Using the idea of reverse solution, the price and demand for new products and reworks under the remanufacturer's leadership model with profits for manufacturers and remanufacturers are as follows:

$$\begin{aligned} p_n^{R*} &= \frac{(1 - \theta)(4 - \theta)Q_0 + (4 - \theta)c_n + (2 - \theta)c_r}{4(2 - \theta)} \\ p_r^{R*} &= \frac{\theta(1 - \theta)Q_0 + \theta c_n + (2 - \theta)c_r}{2(2 - \theta)} \\ q_n^{R*} &= \frac{(1 - \theta)(4 - \theta)Q_0 - (4 - 3\theta)c_n + (2 - \theta)c_r}{4(1 - \theta)(2 - \theta)} \\ q_r^{R*} &= \frac{\theta(1 - \theta)Q_0 + \theta c_n - (2 - \theta)c_r}{4\theta(1 - \theta)} \\ \pi_n^{R*} &= \frac{[(1 - \theta)(4 - \theta)Q_0 - (4 - 3\theta)c_n + (2 - \theta)c_r]^2}{16(1 - \theta)(2 - \theta)^2} \\ \pi_r^{R*} &= \frac{[\theta(1 - \theta)Q_0 + \theta c_n - (2 - \theta)c_r]^2}{8\theta(1 - \theta)(2 - \theta)} \end{aligned} \quad (10)$$

3.1.3. No Leadership Model (NL Model). When the manufacturer and remanufacturer have the same power with no leadership relationship in the market, a game relationship exists between the manufacturer and remanufacturer. The profit expression in this case is

$$\begin{aligned} \max_{p_n} \pi_n^N &= (p_n^N - c_n^N) \left(Q_0 - \frac{p_n^N - p_r^N}{1 - \theta} \right) \\ \max_{p_r} \pi_r^N &= (p_r^N - c_r^N) \left(\frac{\theta p_n^N - p_r^N}{\theta(1 - \theta)} \right) \end{aligned} \quad (11)$$

Through simultaneous solution of the stagnation point, the price and demand for new products and reworks under

the NL model and the profit of manufacturers and remanufacturers, respectively, are as follows:

$$\begin{aligned}
 p_n^{N*} &= \frac{2(1-\theta)Q_0 + 2c_n + c_r}{4-\theta} \\
 p_r^{N*} &= \frac{\theta(1-\theta)Q_0 + \theta c_n + 2c_r}{4-\theta} \\
 q_n^{N*} &= \frac{2(1-\theta)Q_0 - (2-\theta)c_n + c_r}{(1-\theta)(4-\theta)} \\
 q_r^{N*} &= \frac{\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r}{\theta(1-\theta)(4-\theta)} \\
 \pi_n^{N*} &= \frac{[2(1-\theta)Q_0 - (2-\theta)c_n + c_r]^2}{(1-\theta)(4-\theta)^2} \\
 \pi_r^{N*} &= \frac{[\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r]^2}{\theta(1-\theta)(4-\theta)^2}
 \end{aligned} \quad (12)$$

3.2. Government Subsidy Scenario. The government can better encourage the remanufacturing industry by implementing price subsidies for reworks. For the government, subsidy policies are often implemented so as to maximize social welfare. Therefore, this section establishes a two-stage game model for government's price subsidies for remanufacturer units.

Phase 1. The government determines therework unit price subsidy (s) so as to maximize social welfare.

Phase 2. Analyze the competition strategy of manufacturers and remanufacturers under different leadership modes with price subsidy for remanufacturer units.

3.2.1. ML Model under Government Subsidies (Manufacturer Is the Market Leader)

Phase 1. Price subsidy (s) is a known parameter, with the manufacturer first determining the price for new products (p_n^M).

Phase 2. Remanufacturers set the optimal price to maximize their profits considering the demand for new products and reworks in the market.

The profit function of both parties is as follows:

$$\max_{p_r} \pi_r^{M'} = (p_r^M - c_r^M + s) \left(\frac{\theta p_n^M - p_r^M}{\theta(1-\theta)} \right) \quad (13)$$

$$\max_{p_n} \pi_n^{M'}(p_n^M | p_r^M) = (p_n^M - c_n) \left(Q_0 - \frac{p_n^M - p_r^M}{1-\theta} \right) \quad (14)$$

Using the idea of reverse solution, the price and demand for new products and reworks under the manufacturer's

leadership model as well as the profits of manufacturers and remanufacturers are as follows:

$$\begin{aligned}
 p_n^{M**} &= \frac{2(1-\theta)Q_0 + (2-\theta)c_n + c_r - s^*}{2(2-\theta)} \\
 p_r^{M**} &= \frac{2\theta(1-\theta)Q_0 + \theta(2-\theta)c_n + (4-\theta)c_r - (4-\theta)s^*}{4(2-\theta)} \\
 q_n^{M**} &= \frac{2(1-\theta)Q_0 - (2-\theta)c_n + c_r - s^*}{4(1-\theta)} \\
 q_r^{M**} &= \frac{2\theta(1-\theta)Q_0 + \theta(2-\theta)c_n - (4-3\theta)c_r + (4-3\theta)s^*}{4\theta(1-\theta)(2-\theta)} \\
 \pi_n^{M**} &= \frac{[2(1-\theta)Q_0 - (2-\theta)c_n + c_r - s^*]^2}{8(1-\theta)(2-\theta)} \\
 \pi_r^{M**} &= \frac{[2\theta(1-\theta)Q_0 + \theta(2-\theta)c_n - (4-3\theta)c_r + (4-3\theta)s^*]^2}{16\theta(1-\theta)(2-\theta)^2}
 \end{aligned} \quad (15)$$

The government considers price subsidies for remanufacturer units to increase the sales of the remanufactured products as well as maximize social welfare by implementing a price subsidy strategy. In economics, social welfare can often be measured by the total social surplus, which can be expressed by producer surplus plus consumer surplus minus the government subsidies for remanufacturers. In this context, producer surplus is the sum of profit of the manufacturer and remanufacturer, and consumer surplus includes the total surplus of the consumers purchasing new products and reworks. Using TSW to represent social welfare, the government's objective function is as follows:

$$\begin{aligned}
 \max_s \text{TSW} &= \pi_n + \pi_r + CS_n + CS_r - sq_r \\
 &= (p_n - c_n)q_n + (p_r - c_r + s)q_r \\
 &\quad + \left[\frac{Q_0 + (p_n - p_r)/(1-\theta)}{2} - p_n \right] q_n \\
 &\quad + \left[\frac{\theta(p_n - p_r)/(1-\theta) + p_r}{2} - p_r \right] q_r - sq_r \\
 &= \left[\frac{Q_0 + (p_n^M - p_r^M)/(1-\theta)}{2} - c_n \right] q_n^M \\
 &\quad + \left[\frac{\theta(p_n^M - p_r^M)/(1-\theta) + p_r^M}{2} - c_r \right] q_r^M
 \end{aligned} \quad (16)$$

The demand quantity and price in (15) are inserted into (16), to obtain the derivative of price subsidy (s) for the objective function TSW; the derived function is zero, and the

optimal price subsidy amount is (s^*). Thus, the government's optimal price subsidy for reworks in the ML model is

$$s^{M*} = \frac{\{2\theta^2(1-\theta)^2 Q_0 - (2-\theta)[\theta^2(\theta^2 + \theta - 9) + 8\theta]c_n + \{16 + [\theta^3(\theta - 11) + 31\theta^2 - 36\theta]\}c_r - 2\theta^2(1-\theta)(2-\theta)^2\}}{\theta^2(\theta^2 + \theta - 21) + 36\theta - 16} \quad (17)$$

3.2.2. RL Model under Government Subsidies (Remanufacturer Is the Market Leader)

Phase 1. Price subsidy (s) is a known parameter, and the remanufacturer first determines the price of reworks (p_r^R).

Phase 2. Manufacturers set the optimal new product prices to maximize their profits considering the demand of consumers for new products and remanufactured products in the market.

The profit function of both parties is as follows:

$$\max_{p_n} \pi_n^{R'} = (p_n^R - c_n) \left(Q_0 - \frac{p_n^R - p_r^R}{1-\theta} \right) \quad (18)$$

$$\max_{p_r} \pi_r^{R'}(p_r^R | p_n^R) = (p_r^R - c_r + s) \left(\frac{\theta p_n^R - p_r^R}{\theta(1-\theta)} \right) \quad (19)$$

Using the idea of reverse solution, the price and demand for new products and remanufactured products under the remanufacturer leadership model as well as the profits of manufacturers and remanufacturers, respectively, are as follows:

$$\begin{aligned} p_n^{R**} &= \frac{(1-\theta)(4-\theta)Q_0 + (4-\theta)c_n + (2-\theta)c_r - (2-\theta)s^*}{4(2-\theta)} \\ p_r^{R**} &= \frac{\theta(1-\theta)Q_0 + \theta c_n + (2-\theta)c_r - (2-\theta)s^*}{2(2-\theta)} \\ q_n^{R**} &= \frac{(1-\theta)(4-\theta)Q_0 - (4-3\theta)c_n + (2-\theta)c_r - (2-\theta)s^*}{4(1-\theta)(2-\theta)} \end{aligned}$$

$$\begin{aligned} q_r^{R**} &= \frac{\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r + (2-\theta)s^*}{4\theta(1-\theta)} \\ \pi_n^{R**} &= \frac{[(1-\theta)(4-\theta)Q_0 - (4-3\theta)c_n + (2-\theta)c_r - (2-\theta)s^*]^2}{16(1-\theta)(2-\theta)^2} \\ \pi_r^{R**} &= \frac{[\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r + (2-\theta)s^*]^2}{8\theta(1-\theta)(2-\theta)} \end{aligned} \quad (20)$$

At this point, the government's objective function is

$$\begin{aligned} \max_s TSW &= \pi_n + \pi_r + CS_n + CS_r - sq_r \\ &= (p_n - c_n)q_n + (p_r - c_r + s)q_r \\ &\quad + \left[\frac{Q_0 + (p_n - p_r)/(1-\theta)}{2} - p_n \right] q_n \\ &\quad + \left[\frac{\theta(p_n - p_r)/(1-\theta) + p_r}{2} - p_r \right] q_r \\ &\quad - sq_r \\ &= \left[\frac{Q_0 + (p_n^R - p_r^R)/(1-\theta)}{2} - c_n \right] q_n^R \\ &\quad + \left[\frac{\theta(p_n^R - p_r^R)/(1-\theta) + p_r^R}{2} - c_r \right] q_r^R \end{aligned} \quad (21)$$

From the solution idea in Section 2.2.1, the government's optimal price subsidy for remanufactured units under the remanufacturer leadership model is as follows:

$$s^{R*} = \frac{[-\theta^2(1-\theta)Q_0 + \theta(2\theta^2 - 9\theta + 8)c_n + (2\theta^3 - 9\theta^2 + 14\theta - 8)c_r + 2\theta^2(1-\theta)(2-\theta)]}{(2\theta^2 - 7\theta + 4)(2-\theta)} \quad (22)$$

3.2.3. NL Model under Government Subsidies (No Leadership Model). When the manufacturer and remanufacturer have the same power with no leadership relationship, a game relationship exists between the manufacturer and remanufacturer in the market. The profit expression is as follows:

$$\begin{aligned} \max_{p_n} \pi_n^N &= (p_n^N - c_n) \left(Q_0 - \frac{p_n^N - p_r^N}{1-\theta} \right) \\ \max_{p_r} \pi_r^N &= (p_r^N - c_r + s) \left(\frac{\theta p_n^N - p_r^N}{\theta(1-\theta)} \right) \end{aligned} \quad (23)$$

With price subsidy $s > 0$ as known parameter, the price and demand for new products and reworks as well as the profit of manufacturers and remanufacturers under the NL model are obtained by solving the stagnation point in a joint mode, as follows:

$$\begin{aligned} p_n^{N**} &= \frac{2(1-\theta)Q_0 + 2c_n + c_r - s^*}{4-\theta} \\ p_r^{N**} &= \frac{\theta(1-\theta)Q_0 + \theta c_n + 2c_r - 2s^*}{4-\theta} \end{aligned}$$

$$\begin{aligned}
q_n^{N**} &= \frac{2(1-\theta)Q_0 - (2-\theta)c_n + c_r - s^*}{(1-\theta)(4-\theta)} \\
q_r^{N**} &= \frac{\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r + (2-\theta)s^*}{\theta(1-\theta)(4-\theta)} \\
\pi_n^{N**} &= \frac{[2(1-\theta)Q_0 - (2-\theta)c_n + c_r - s^*]^2}{(1-\theta)(4-\theta)^2} \\
\pi_r^{N**} &= \frac{[\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r + (2-\theta)s^*]^2}{\theta(1-\theta)(4-\theta)^2}
\end{aligned} \quad (24)$$

Now, the government's objective function is

$$\begin{aligned}
\max_s TSW &= \pi_n + \pi_r + CS_n + CS_r - sq_r \\
&= (p_n - c_n)q_n + (p_r - c_r + s)q_r \\
&\quad + \left[\frac{Q_0 + (p_n - p_r)/(1-\theta)}{2} - p_n \right] q_n \\
&\quad + \left[\frac{\theta(p_n - p_r)/(1-\theta) + p_r}{2} - p_r \right] q_r - sq_r \quad (25) \\
&= \left[\frac{Q_0 + (p_n^N - p_r^N)/(1-\theta)}{2} - c_n \right] q_n^N \\
&\quad + \left[\frac{\theta(p_n^N - p_r^N)/(1-\theta) + p_r^N}{2} - c_r \right] q_r^N
\end{aligned}$$

From the solution method in Section 3.2.1, the government can obtain the optimal price subsidy for a remanufactured unit under the no-market leadership model as follows:

$$\begin{aligned}
s^{N*} &= \frac{[\theta^2(1-\theta)Q_0 - 2\theta(2-\theta)c_n + (4-3\theta+\theta^2)c_r]}{(3\theta-4)} \quad (26)
\end{aligned}$$

4. Result Analysis

To facilitate this analysis, the above results are organized as in Tables 2, 3, and 4.

Proposition 1. *Under different market leadership models, (1) the new product and rework prices are lower with government subsidies rather than without government subsidies; (2) the manufacturers' new product sales and profits are lower with government subsidies rather than without government subsidies; (3) the remanufacturers' rework product sales volume and profits are higher with government subsidies rather than without government subsidies.*

Proof. The p_n^* , p_r^* , q_n^* , q_r^* , π_n^* , π_r^* after government subsidy in Tables 2, 3, and 4 minus p_n , p_r , q_n , q_r , π_n , π_r before government subsidy and analyze the results, since the government subsidy $s > 0$, (1) and (2) and (3) can be proved. $\square$

From Proposition 1, government subsidies in the *ML* and *NL* models reduce the price of reworks to a certain extent, but simultaneously increase the sales volume of remanufactured products, thus effectively curbing the dominant and monopoly position of manufacturers and increasing market competitiveness of remanufactured products; government subsidies in the *RL* model impact the manufacture of new products and consolidate the market leadership of remanufacturers.

Proposition 2. *Under different market models, when the government subsidizes the price of remanufactured products for remanufacturers, the actual price of the remanufactured product keeps on rising.*

Proof. When the government subsidizes the price of remanufactured units, the actual price of the remanufactured product obtained by the remanufacturer is $p_r^* + s^*$. With the government-subsidized reworks' prices p_r^* in Tables 2, 3, and 4 plus government subsidies per unit of remanufactured product s^* , minus the price of reworks before government subsidies p_r , the following results are obtained:

ML mode: $p_r^{M*} + s^{M*} - p_r^M = ((4-3\theta)/4(2-\theta))s^{M*} > 0$

RL mode: $p_r^{R*} + s^{R*} - p_r^R = (1/2)s^{R*} > 0$

NL mode: $p_r^{N*} + s^{N*} - p_r^N = ((2-\theta)/(4-\theta))s^{N*} > 0$, thus proving the conclusion $\square$

From Proposition 2, once the government subsidizes the unit product price of the remanufactured product, from the consumers' perspective, the price of the remanufactured product becomes lower than the price without government subsidies; for the remanufacturer, government subsidies lead to a decline in price of reworks. However, the remanufactured products' actual price rises after accepting government subsidies. This shows that government subsidies can stimulate consumer demand for remanufactured products through "low price means", while helping the remanufacturers increase the profit of remanufactured products and thus promoting remanufacturing.

Proposition 3. *In different market models, the sales of new products are inversely related to government subsidies; and the sales of reworks are positively related to government subsidies.*

Proof. The first-order partial derivatives of s are obtained from government subsidies q_n , q_r in Tables 2, 3, and 4, respectively. The results are as follows:

$$\frac{dq_n^{M*}}{ds^*} = \frac{-1}{4(1-\theta)} < 0,$$

$$\frac{dq_n^{R**}}{ds^*} = \frac{-(2-\theta)}{4(1-\theta)(2-\theta)} < 0,$$

$$\frac{dq_n^{N***}}{ds^*} = \frac{-1}{(1-\theta)(4-\theta)} < 0$$

$$\frac{dq_r^{M*}}{ds^*} = \frac{4-3\theta}{4\theta(1-\theta)(2-\theta)} > 0,$$

TABLE 2: The changes in remanufacturing supply chain decisions before and after government subsidies in ML model.

Variable	Before government subsidies	After government subsidies
p_n^{M*}	$\frac{2(1-\theta)Q_0 + (2-\theta)c_n + c_r}{2(2-\theta)}$	$\frac{2(1-\theta)Q_0 + (2-\theta)c_n + c_r - s^{M*}}{2(2-\theta)}$
p_r^{M*}	$\frac{2\theta(1-\theta)Q_0 + \theta(2-\theta)c_n + (4-\theta)c_r}{4(2-\theta)}$	$\frac{2\theta(1-\theta)Q_0 + \theta(2-\theta)c_n + (4-\theta)c_r - (4-\theta)s^{M*}}{4(2-\theta)}$
q_n^{M*}	$\frac{2(1-\theta)Q_0 - (2-\theta)c_n + c_r}{4(1-\theta)}$	$\frac{2(1-\theta)Q_0 - (2-\theta)c_n + c_r - s^{M*}}{4(1-\theta)}$
q_r^{M*}	$\frac{2\theta(1-\theta)Q_0 + \theta(2-\theta)c_n - (4-3\theta)c_r}{4\theta(1-\theta)(2-\theta)}$	$\frac{2\theta(1-\theta)Q_0 + \theta(2-\theta)c_n - (4-3\theta)c_r + (4-3\theta)s^{M*}}{4\theta(1-\theta)(2-\theta)}$
π_n^{M*}	$\frac{[2(1-\theta)Q_0 - (2-\theta)c_n + c_r]^2}{8(1-\theta)(2-\theta)}$	$\frac{[2(1-\theta)Q_0 - (2-\theta)c_n + c_r - s^{M*}]^2}{8(1-\theta)(2-\theta)}$
π_r^{M*}	$\frac{[2\theta(1-\theta)Q_0 + \theta(2-\theta)c_n - (4-3\theta)c_r]^2}{16\theta(1-\theta)(2-\theta)^2}$	$\frac{[2\theta(1-\theta)Q_0 + \theta(2-\theta)c_n - (4-3\theta)c_r + (4-3\theta)s^{M*}]^2}{16\theta(1-\theta)(2-\theta)^2}$

TABLE 3: The changes in remanufacturing supply chain decisions before and after government subsidies in RL model.

Variable	Before government subsidies	After government subsidies
p_n^{R*}	$\frac{(1-\theta)(4-\theta)Q_0 + (4-\theta)c_n + (2-\theta)c_r}{4(2-\theta)}$	$\frac{(1-\theta)(4-\theta)Q_0 + (4-\theta)c_n + (2-\theta)c_r - (2-\theta)s^{R*}}{4(2-\theta)}$
p_r^{R*}	$\frac{\theta(1-\theta)Q_0 + \theta c_n + (2-\theta)c_r}{2(2-\theta)}$	$\frac{\theta(1-\theta)Q_0 + \theta c_n + (2-\theta)c_r - (2-\theta)s^{R*}}{2(2-\theta)}$
q_n^{R*}	$\frac{(1-\theta)(4-\theta)Q_0 - (4-3\theta)c_n + (2-\theta)c_r}{4(1-\theta)(2-\theta)}$	$\frac{(1-\theta)(4-\theta)Q_0 - (4-3\theta)c_n + (2-\theta)c_r - (2-\theta)s^{R*}}{4(1-\theta)(2-\theta)}$
q_r^{R*}	$\frac{\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r}{4\theta(1-\theta)}$	$\frac{\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r + (2-\theta)s^{R*}}{4\theta(1-\theta)}$
π_n^{R*}	$\frac{[(1-\theta)(4-\theta)Q_0 - (4-3\theta)c_n + (2-\theta)c_r]^2}{16(1-\theta)(2-\theta)^2}$	$\frac{[(1-\theta)(4-\theta)Q_0 - (4-3\theta)c_n + (2-\theta)c_r - (2-\theta)s^{R*}]^2}{16(1-\theta)(2-\theta)^2}$
π_r^{R*}	$\frac{[\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r]^2}{8\theta(1-\theta)(2-\theta)}$	$\frac{[\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r + (2-\theta)s^{R*}]^2}{8\theta(1-\theta)(2-\theta)}$

TABLE 4: The changes in remanufacturing supply chain decisions before and after government subsidies in NL model.

Variable	Before government subsidies	After government subsidies
p_n^{N*}	$\frac{2(1-\theta)Q_0 + 2c_n + c_r}{4-\theta}$	$\frac{2(1-\theta)Q_0 + 2c_n + c_r - s^{N*}}{4-\theta}$
p_r^{N*}	$\frac{\theta(1-\theta)Q_0 + \theta c_n + 2c_r}{4-\theta}$	$\frac{\theta(1-\theta)Q_0 + \theta c_n + 2c_r - 2s^{N*}}{4-\theta}$
q_n^{N*}	$\frac{2(1-\theta)Q_0 - (2-\theta)c_n + c_r}{(1-\theta)(4-\theta)}$	$\frac{2(1-\theta)Q_0 - (2-\theta)c_n + c_r - s^{N*}}{(1-\theta)(4-\theta)}$
q_r^{N*}	$\frac{\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r}{\theta(1-\theta)(4-\theta)}$	$\frac{\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r + (2-\theta)s^{N*}}{\theta(1-\theta)(4-\theta)}$
π_n^{N*}	$\frac{[2(1-\theta)Q_0 - (2-\theta)c_n + c_r]^2}{(1-\theta)(4-\theta)^2}$	$\frac{[2(1-\theta)Q_0 - (2-\theta)c_n + c_r - s^{N*}]^2}{(1-\theta)(4-\theta)^2}$
π_r^{N*}	$\frac{[\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r]^2}{\theta(1-\theta)(4-\theta)^2}$	$\frac{[\theta(1-\theta)Q_0 + \theta c_n - (2-\theta)c_r + (2-\theta)s^{N*}]^2}{\theta(1-\theta)(4-\theta)^2}$

TABLE 5: The results before and after government price subsidies in ML model: a comparison.

Variable	Before price subsidy	After price subsidy	Comparison of results
p_n^M	55528	42981	↓
p_r^{M*}	24859	3527	↓
q_n^{M*}	23325	1366	↓
q_r^{M*}	35244	92755	↑
π_n^{M*}	3.11E + 08	1.07E + 06	↓
π_r^{M*}	2.98E + 08	2.06E + 09	↑
s	—	35134.0	—
$\pi_n^{M*} + \pi_r^{M*}$	6.09E + 08	2.06E + 09	↑
cs_n	7.65E + 08	7.70E + 07	↓
cs_r	9.13E + 08	4.25E + 09	↑
$cs_n + cs_r$	8.42E+08	5.16E+09	↑

TABLE 6: The results before and after government price subsidy in RL model: a comparison.

Variable	Before price subsidy	After price subsidy	Comparison of results
p_n^{R*}	54007	43646	↓
p_r^{R*}	25814	5092	↓
q_n^{R*}	29518	3615	↓
q_r^{R*}	27458	87898	↑
π_n^{R*}	3.49E + 08	5.23E + 06	↓
π_r^{R*}	2.59E + 08	2.65E + 09	↑
s	—	41444.5	—
$\pi_n^{R*} + \pi_r^{R*}$	6.08E + 08	2.65E + 09	↑
cs_n	9.22E + 08	1.97E + 08	↓
cs_r	6.13E + 08	4.01E + 09	↑
$cs_n + cs_r$	1.12E + 09	4.62E + 09	↑

$$\frac{dq_r^{R**}}{ds^*} = \frac{2 - \theta}{4\theta(1 - \theta)} > 0,$$

$$\frac{dq_r^{N***}}{ds^*} = \frac{2 - \theta}{\theta(1 - \theta)(4 - \theta)} > 0$$
(27)

thus proving the conclusion. $\square$

Proposition 3 shows that the government's price subsidy for remanufactured products effectively stimulates the consumers' demand for reworks. However, as government subsidies continue to increase, the sales of new products will decrease but the sales of remanufactured products will increase. Under the *ML* model, the government can effectively curb the monopoly of the new product market and increase the market competitiveness of reworks by increasing the subsidies for reworks. In the *RL* model, the higher the government subsidies for reworks, the more stable is the remanufacturer's market leadership position. In the *NL* model, the price advantage of reworks in market competition is reflected by government subsidies. The greater the government subsidies, the greater are the price advantages.

5. Numerical Simulation and Analysis

In a different market leadership model, the influence of consumer environmental preferences on the decision variables, profits, government subsidies, and social welfare of

manufacturers and remanufacturers can become more complicated. Therefore, this study uses numerical simulation to conduct analysis. The simulation analysis covers two aspects: (1) analysis of the variable results before and after government subsidies and (2) analysis of the impact of consumer environmental preferences on various variables.

First, the relevant parameters are assigned. This paper assumes that the manufacturing cost of the new product is $c_n = 42,200$, the manufacturing cost of the remanufactured product is $c_r = 16,400$, and the market capacity is $Q_0 = 100,000$.

5.1. Simulation Results before and after Government Subsidies: A Comparative Analysis. Setting the consumers' environmental preference coefficient at $\theta = 0.6$, calculate the optimal price subsidy s in different market leadership models with known data using MATLAB calculation. While s in the *ML* model is 35134.0, S in the *RL* mode is 41444.5, and S in the *NL* model is 6596.4.

Tables 5, 6, and 7 clearly show that the changes in variables before and after subsidy are consistent with the proposition analysis results obtained in the third section. After the government implements price subsidy, the overall profit on the closed-loop supply chain composed of manufacturers and remanufacturers will be found to increase under different market leadership models, with a fall in total surplus of consumers purchasing new products. However, the total consumer surplus for remanufactured products as well as

TABLE 7: The results before and after government price subsidies in the NL model: a comparison.

Variable	Before price subsidy	After price subsidy	Comparison of results
p_n^{N*}	53176	51236	↓
p_r^{N*}	24153	20273	↓
q_n^{N*}	27441	22591	↓
q_r^{N*}	32304	43621	↑
π_n^{N*}	3.01E + 08	2.04E + 08	↓
π_r^{N*}	2.50E + 08	4.57E + 08	↑
s	—	6596.4	—
$\pi_n^{M*} + \pi_r^{M*}$	5.51E + 08	6.61E + 08	↑
cs_n	9.08E + 08	8.46E + 08	↓
cs_r	3.13E + 08	5.71E + 08	↑
$cs_n + cs_r$	1.22E + 09	1.42E + 09	↑

FIGURE 2: The product price trend chart.

the overall total consumer surplus will increase. This clearly demonstrates that government price subsidies encourage the sale of remanufactured products, promote the development of remanufacturing, and have a positive impact on social welfare.

5.2. Simulation Results on Consumer Environmental Preferences. The simulation before and after government subsidy shows the consumer environmental preference coefficient θ to be 0.6. To ensure that the results of each variable are positive when analyzing the impact of consumer environmental preferences, the range of consumer environmental preference coefficients is taken as $\in [0.45, 0.7]$.

5.2.1. Impact of Consumer Environmental Preference on Product Price and Sales Volume. Figures 2 and 3 show that the sales price of new products will increase, whereas the sales price of remanufactured products will decrease, with the increase in consumer environmental awareness. Furthermore, the demand for new products will decrease, whereas

the demand for remanufactured products will increase, as the consumer environmental awareness increases. Therefore, when the consumer environmental awareness continues to increase, the manufacturers and remanufacturers will adopt different pricing strategies for products. Due to lower consumer demand for new products, new product manufacturers often adopt a “price increase” strategy to achieve few sales but not “disadvantage” status in order to achieve higher profits. As the consumer demand for remanufactured products increases, the remanufacturers increase their remanufactured product market share through appropriate “price reduction” strategies.

The new product has the highest price in the *ML* model, second largest price in the *RL* model, and the lowest price in the *NL* model. However, for the rework, the highest price is in the *RL* model, the second largest price is in the *ML* model, and the lowest price in the *NL* model. Thus, for consumers, new products are more attractive in the *RL* model than in the *ML* model, while consumers can buy new products with the least amount of money in the *NL* model. While

FIGURE 3: The product sales trend chart.

FIGURE 4: The main profit trend chart.

remanufactured products are attractive in the *ML* model, consumers can buy them at the lowest price in the *NL* model.

The demand for new products is the highest in the *RL* model, second largest in the *NL* model, and lowest in the *ML* model. For remanufactured products, the demand is highest in the *ML* model, second highest in the *NL* model, and lowest in the *RL* model. Thus, consumers have different needs for products under different leadership models. Because of the excessive price of remanufactured products, the consumers' demand for new products is accelerated in the *RL* model. The "high" price of new products has led

consumers to increase their demand for remanufactured products in the *ML* model. This verifies hypothesis 3, proving the phenomenon of "replace each other, one increases and one decreases" between new products and rework products.

5.2.2. Impact of Consumer Environmental Preference on Manufacturer and Remanufacturer Profits. In Figure 4, the manufacturers' profits will always decrease as the consumers' environmental preferences increase under different market leadership models, but the remanufacturers' profits will increase as the consumers' environmental preferences increase. From

FIGURE 5: The social welfare trend chart.

this result and the conclusions of Section 5.2.1, double decline has led to a decline in profits for new product manufacturers. For remanufacturers, the price for rework is far lower than the price for new products, and is stable and rising, but not capable of surpassing the price of new products; however, the profits for remanufactured products will increase with the increase in their sales.

From Figure 4, the manufacturer has the highest profit in the *RL* model, followed by the *ML* model, with the lowest profit in the *NL* model. As regards the remanufacturers, the *ML* model shows the highest profit, the *RL* model shows the second largest profit, and the *NL* model shows the lowest profit. Thus, the *ML* and *RL* models improve the profit margin of the manufacturers as well as remanufacturers. Under the *NL* model, in case of competition between manufacturers and remanufacturers, both parties may decide to “go to the same,” that is, reduce their part of the profit to seize the market share.

5.2.3. Impact of Consumer Environmental Preference on Social Welfare. In Figure 5, in *ML* and *NL* models, social welfare will increase as consumers’ environmental preferences increase, while social welfare developed in two stages under *RL* model, first increasing with an increase in consumer environmental preferences and then sharply declining. Furthermore, the *RL* model shows higher social welfare than that brought in by the *ML* and *NL* models up to a certain consumer environmental preference level, but once that level is exceeded, the *RL* model brings no positive social welfare.

5.2.4. Impact of Consumer Environmental Preference on Government Subsidies. Figure 6 shows that, regardless of the market leadership model, government subsidies increase with the increase in consumer environmental preferences. From the

analysis of the expression of government subsidies according to the actual conditions of the remaining parameters (including new product costs, rework costs, and market capacity), the figure shows the scope of changes in various parameters impacting government subsidies. Finally, the government’s optimal subsidies under different market leadership models are ranked as $RL \geq ML \geq NL$. Obviously, the *RL* model can attract more government subsidies, and combined with the characteristics of “low price, high demand” for remanufactured products will undoubtedly bring lucrative profits to remanufacturers, thus making remanufacturing more competitive.

6. Conclusions

This study examines a closed-loop supply chain system involving a manufacturer and an independent remanufacturer. Game analysis and numerical simulation methods are used to study the changes in decision-making of supply chain entities in different market leadership models before and after government subsidies. The study analyzes the impact of consumer environmental preferences on product prices, demand, subjective profits, government subsidies, and social welfare under different market leadership models. The main conclusions of the study are as follows:

(1) Government subsidies have reduced the selling price of remanufactured products to a certain extent, raised the demand for rework products, and increased the final income of remanufacturers receiving government subsidies, effectively curbing the market monopoly of manufacturers. (2) Regardless of market leadership model, the sales price of new products will increase, and that of remanufactured products will decrease, as the consumers’ environmental awareness increases. (3) Market leaders are more conducive to improve

FIGURE 6: The government subsidy trend chart.

profit margins. Without market leaders, decisions can lead to “both sides suffered great losses”. (4) Social welfare and government subsidies can to a certain extent increase with the increase in consumer environmental preferences.

The conclusions of this study give rise to the following suggestions. The government should formulate subsidy policies for remanufacturing enterprises according to the market leadership model to promote the remanufacturing industry and strive to improve consumers’ environmental awareness. Remanufacturing companies should continuously improve their technology, strive to improve the quality of remanufactured products, and work hard to increase the consumer acceptance of rework products, to ultimately bring more benefits.

A future study can better simulate reality by considering multiple manufacturer and remanufacturer agents in model improvement. Different subsidy strategies can also be discussed for an in-depth analysis of government policies.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Conflicts of Interest

The authors declare no conflicts of interest.

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