Research on Product Upgrading Strategy in Remanufacturing Environment

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Abstract: Under the manufacturers and outsourcing authorizing remanufacturing, the production decisions considering the optimal production decision is made under a two-stage game model in which the manufacturer engages in both new product production and discarded product remanufacturing. The competitive and cooperative relationship between manufacturer and who then charge a certain remanufacturing licensing fee to third party remanufacturers is analyzed, and the differences between models M and O in terms of optimal production quantity of new/remanufactured products, economic performance, environmental sustainability and product upgrading incentives are compared. We find that manufacturer are more likely to upgrade products when the remanufacturing is outsourced to a third party remanufacturer. When the remanufacturing business is outsourced, the third party remanufacturer always reduces the profitability of the original product manufacturer, but it is beneficial to the environment.
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Introduction

Environmental and resource issues have become the common concern of all mankind. Improving the green production of manufacturing industry and vigorously developing green remanufacturing industry are important ways to solve this problem. According to statistics, green remanufacturing can reduce energy consumption by 50%, consumables by 85% and labor value by 33% on average. How to realize the harmonious development of nature and society is a serious challenge facing human society. Therefore, the development strategy of sustainable development has been paid more and more attention by governments and enterprises around the world. Reverse Supply Chain (RSC), as a modern manufacturing management mode that comprehensively considers the recycling and final disposal of waste products, is not only an important part of sustainable development, but also a sustainable development mode of sustainable development strategy in manufacturing industry. As an important link of reverse supply chain, Remanufacturing is an important way to realize the reuse of retired products and sustainable economic development. Many original product manufacturers have regarded remanufacturing as an indispensable part of their business model [1]. Remanufacturing is a series of manufacturing processes that turn parts or products at the end of their life cycle into new or restored products by processing them again.

In the context of green and sustainable development, the Design for environment (DfE) strategy of supply chain has attracted extensive attention from scholars at home and abroad. Raz et al. [2] proposed the concept of environmental design earlier, pointing out that enterprises can reduce the environmental impact and production cost of unit products through environmental design. Zheng et al. [3] studied the impact of manufacturers' environmental design level on enterprises' production decisions and the environment under the conditions of monopoly and competition respectively. Li Jingjing et al. [4] studied the incentive mechanism of enterprise eco-design, and showed that increasing confidence sharing degree can improve the benefit distribution and eco-design effort level of supply chain enterprises. In terms of product design, Wu[5] and Xiao Lu et al. [6] studied the product design and government incentive of two-cycle closed-loop supply chain. Liu et al. [7] studied the impact of product design strategy on supply chain operation under the premise of component design by suppliers and product design by manufacturers. Li et al. [8] analyzed the influence of product design and advertising strategy of direct selling closed-loop supply chain on the decision-making of member enterprises. In terms of remanufacturing design, Xia Xiqiang et al. [9] compared the impact of remanufacturing design cost borne by the manufacturer or the manufacturer on the degree of remanufacturing design, recovery rate and enterprise performance. Reimann et al. [10] studied the impact of manufacturer and retailer's responsibility for remanufacturing on remanufacturing process innovation.

Although remanufacturing can bring many benefits to original product manufacturers, it also brings a series of challenges, the most prominent of which is that remanufactured products will erode the market share of new products, and even affect the brand and profit of original product manufacturers, because consumers generally believe that the value of remanufactured products is 15.3% lower than that of new products [11]. More worrisome is that many consumers associate cheap remanufactured products with the manufacturer's brand, tarnish its product image [12]. Therefore, many manufacturers do not carry out remanufacturing themselves, but outsource the remanufacturing business to independent third party remanufacturers [13]. In order to cope with the erosion of new products by remanufactured products, manufacturers often adopt the following strategies: First, some manufacturers do not engage in remanufacturing activities themselves, but instead outsource them to independent third party remanufacturers. Second, whether the original product manufacturer is engaged in remanufacturing or outsourcing it, many original product manufacturers increase their innovation investment in new products, so as to distinguish the innovative new products from the remanufactured products to the greatest extent and reduce the erosion problem caused by the remanufactured products. The results provide scientific decision-making reference for how product upgrading strategy affects environmental sustainability and product upgrading strategy of manufacturers.

1. Problem description and hypothesis

Is the q_n product upgrade strategy the best decision for the remanufacturing business? What is the specific impact of product upgrade strategy? From an economic point of view, the product upgrading strategy of original product manufacturers seems to reduce the erosion of new products. However, from an environmental point of view, the product upgrading decision is not always environmentally friendly. It takes a long R&D period from product R&D to market launch. Referring to the literature study of [14-19], it is assumed that in the first stage of the game, manufacturers decide whether to upgrade products or not; In the second stage of the game, the manufacturer decides the remanufacturing license fee f to the third party remanufacturer, and then they simultaneously determine the optimal production quantity of new products and remanufactured products q_r. It is assumed that the manufacturer can decide whether to upgrade the product in stage 1, so if the manufacturer does not invest in R&D, there will be better quality upgraded products in the market in stage 2. Therefore, it is considered that there are only two types of products in the market after remanufacturing: one is new products (if the manufacturer does not invest in R&D, it is general new products, otherwise it is upgraded products); The other is the remanufactured products that are remanufactured after the new products become old. Assume that there is a vertical quality difference between the upgraded product and the general new product. If the original product manufacturer introduces the upgraded product, it will increase the consumer's valuation of the product to the point $\theta = 1 + \delta$, where $\delta > 0$ denotes the quality difference between the upgraded product and the general new product. Here the quality of the general new product has been normalized to 1. Assume that the expense function for investing in product upgrades is a convex function $K(\theta - 1)^2/2$. Cost functions with similar structures have been widely used in product R&D and quality improvement literature (Vives[20],Yin et al.[21]). From the consumption function, it can be seen that if the original product manufacturer does not upgrade the product, the quality of the general new product is $\theta = 1$, and the corresponding R&D expense is 0. In order to highlight the difference in cost between manufacturing and remanufacturing, assumed that the production cost of new products is and the production cost of remanufactured products is [22]. Since the cost of remanufacturing is much lower than that of manufacturing new products in practice, for the convenience of analysis, it is further assumed that the production cost of remanufactured products can be ignored compared with that of new products [23-25], i.e. $c_n = c > c_r = 0$.

Considering that consumers' willingness to pay for new products and remanufactured products is usually inconsistent, the defined parameter v_n represents consumers' valuation of new products, which is uniformly distributed between 0 and 1. The net utility of a consumer of type is dependent on both her valuation of the new product and its price, i.e. $U_n = \theta v_n - p_n$

In stage 2, both new and remanufactured goods exist in the market.To characterize their product erosion effect, it is assumed that consumers value the remanufactured goods as kv_n, where is the value discount that consumers place on the remanufactured goods [26]. Therefore, the net utility of purchasing remanufactured goods for consumers of type is $U_r = kv_n - p_r$. Two utility indifference points can then be obtained: (1) some consumers make no difference between buying the new product and the remanufactured product, i.e. $U_n = \theta v_n - p_n = U_r = kv_n - p_r$,and (2) some consumers have no difference between buying the remanufactured product and not buying the product, i.e. $U_r = kv_n - p_r = 0$ .Based on the indifference point of consumers' utility between the new product and the remanufactured product and the indifference point of consumers' utility between the remanufactured product and the non-purchased product, their inverse demand functions can be derived as follows:

$$p_n = \theta(1 - q_n) - kq_r$$
$$p_r = k(1 - q_n - q_r) \qquad (1)$$

The parameters in the expression of inverse demand function for new products in Equation (1) represent the quality difference between general new products and upgraded products. is the general new product; And then indicates that the original product manufacturer has upgraded the new product, which in turn leads to the improvement of the quality of the new product. The greater , the greater the upgrade degree of the new product by the manufacturer, that is, the greater the difference between the old and new product.

2. Model establishment and solution

Model M represents that the original product manufacturer engages in remanufacturing itself; Model O means that the remanufacturing is outsourced to an independent third party remanufacturer, and the original product manufacturer charges the third party remanufacturer a certain remanufacturing license fee. Then we compare the differences between Model M and Model O in terms of optimal production quantity, economic performance, environmental sustainability and product upgrade incentive. These include:

（1） Are there differences between types M and O in terms of incentives to upgrade their products?

（2） Which strategy is economically more beneficial for the original manufacturer versus outsourcing to a third party remanu facturer?

（3） Which strategy is better for the environment from a sustainability perspective?

（4） What is the impact of the product upgrade strategy on the optimal decision aspects of the relevant decision-making agents?

2.1 manufacturer engaged in Remanufacturing (Model M)

Suppose that the original product manufacturer can decide whether to upgrade the product in stage 1. If the original product manufacturer does not invest in R&D, only the original new product will be in the market in stage 2. However, if the manufacturer decides to invest in R&D, a better quality upgraded product will be available in the stage 2 market. Therefore, there are two types of products in the stage 2 market: first, new products (general new products or upgraded products); The other is the discarded new products that are remanufactured.

In Model M, the original product manufacturer will recycle and remanufacture the waste products in cycle 1 while making the product upgrade decision. Therefore, in Model M, the manufacturer's decision-making sequence is as follows: in the first stage, the manufacturer makes the decision of product upgrade. After making the decision of whether to upgrade the product, in the second stage, the manufacturer will make the decision of optimal output for new products and remanufacturing respectively.

The definition represents the profit of decision maker i ∈ {m,o} in model j ∈ {M and O}, where the subscripts i ∈ {m and o} represent the original product manufacturer and the outsourcing third party remanufacturer respectively, and the subscripts j ∈ {M and O} represent the model M and O respectively.In stage 1, manufacturers decide whether or not to invest in product upgrade; Then in stage 2, the manufacturer determines the optimal production quantities of the new product and the remanufactured product q_r.

Since both the new products and the remanufactured products are provided by the original product manufacturer, the decision problem can be formulated as follows:

$$\max_{q_n, q_r} \pi_0^M(\theta, q_n, q_r) = (p_n - c)q_n + p_r q_r - K(\theta - 1)^2/2 \quad (2\text{-}1)$$

The first term in Equation (2-1) is the original product manufacturer's profit from selling new products, the second term is its profit from remanufacturing, and the final item is the potential cost of investing in product research and development.

In order to analyze the impact of product upgrading on the equilibrium outcome, it is necessary to compare the profit of the original product manufacturer with or without investment in product R&D. To this end, the inverse demand functions for new products and remanufactured products in Equation (1) are substituted into Equation (2-1). Then the original product manufacturer's decision problem can be rewritten as follows:

$$\max_{q_n, q_r} \pi_0^M(\theta, q_n, q_r) = (\theta(1-q_n) - kq_r - c)q_n + k(1-q_n-q_r)q_r - K(\theta-1)^2/2$$

The Hessian matrix of the above equation can be obtained as

$$H_2 = \begin{vmatrix} \frac{\partial^2 \pi_0^M}{\partial q_n^2} & \frac{\partial^2 \pi_0^M}{\partial q_n \partial q_r} \\ \frac{\partial^2 \pi_0^M}{\partial q_n \partial q_r} & \frac{\partial^2 \pi_0^M}{\partial q_r^2} \end{vmatrix} = \begin{vmatrix} -2\theta & -2k \\ -2k & -2k \end{vmatrix}$$

Since $\theta \geq 1, 0 < k < 1$, the above first-order Hessian matrix $H_1 < 0$, the second-order Hessian matrix $H_2 = 4k(\theta - k) > 0$

That is, there is always an optimal production quantity and such that the above equation has a maximum value. Using the first-order partial derivative method, the optimal quantities of the original product manufacturer to produce new products and remanufactured products can be obtained as follows:

$$q_n^{M*} = \frac{\theta - k - c}{2(\theta - k)}$$

$$q_r^{M*} = \frac{\theta - k}{2c}$$

Substituting the optimal production quantities of new products and remanufactured products back into the profit function of the original product manufacturer, the optimal profit can be obtained as follows:

$$\pi_0^{M*} = \frac{\theta^2 + c^2 + 2\theta c - 2\theta c - \theta k}{4(\theta - k)} - K(\theta - 1)^2/2$$

Let $\pi_0^{M*}(\theta = 1) = \pi_0^{M*}(\theta = 1 + \delta)$, it can be seen that there is a threshold for the cost of product upgrade, $K < K^M$ which is obviously preferred $\theta = 1 + \delta$ by the original product manufacturer , and the original product manufacturer will invest in product upgrade at the first stage; While $K > K^M$, the result is the opposite. All optimal decisions and profits of the original product manufacturer in Model M are shown in the following table 1:

Table 1 manufacturer's optimal decision and profit for remanufacturing (Model M)

Optimal number of new products: $q_n^{M*} = \frac{\theta-k-c}{2(\theta-k)}$
Optimal quantity of remanufactured products: $q_r^{M*} = \frac{\theta-k}{2c}$
Optimal profit: $\pi_0^{M*} = \frac{\theta^2+c^2+2\theta c-2\theta c-\theta k}{4(\theta-k)} - K(\theta-1)^2/2$
Threshold of K: $K^M = \frac{\theta+k^2-\theta k-k-c^2}{2(\theta-1)(\theta-k)(1-k)}$

2.2 Outsourcing a third party remanufacturer to engage in remanufacturing (Model O)

Despite the profitability of remanufacturing, consumers generally value remanufactured goods at 15.3 % less than new products. Even many consumers associate cheap remanufactured goods with the brand of the original product manufacturer, tarnishing its brand image. As a result, many original product manufacturers no longer carry out remanufacturing themselves, but outsource the remanufacturing business to independent third party manufacturers.

Suppose that there is an original product manufacturer in the market, which can decide whether to invest in upgrading the new product and outsource the remanufacturing business to the third party manufacturer. The game sequence of Model O is as follows: in the first stage, the original product manufacturer decides whether to invest in upgrading the product; In the second stage, the manufacturer determines the remanufacturing license fee f to the third party remanufacturer, and then the manufacturer and the third party remanufacturer simultaneously decide the optimal production quantities of new products and remanufactured products q_r.

Therefore, the decision problems of the original product manufacturer and the third party remanufacturer in the second stage are as follows:

$$\max_{f,q_n} \pi_0^O = (p_n - c)q_n + fq_r - K(\theta - 1)^2/2$$

$$\max_{q_r} \pi_t^O = (p_r - f)q_r \qquad (2\text{-}2)$$

Equation (1) can be substituted into Equation (2-2) to obtain the optimal production quantity of new products and remanufactured products can be obtained by solving the first-order conditions simultaneously

$$q_n^{O*} = \frac{2\theta - k + f - 2c}{4\theta - k}$$

$$q_r^{O*} = \frac{ck + k\theta - 2\theta f}{k(4\theta - k)}$$

Substituting and back into the profit function of the original product manufacturer and using the first-order condition for f, the optimal licensing fee can be obtained as

$$f^* = \frac{8\theta^2 - 3\theta k - ck}{2\theta(8\theta - 3k)k}$$

Finally, substituting q_n^{O*} 、 q_r^{O*} and back into the profit functions of the manufacturer and the third-party remanufacturer, we can obtain their optimal profits as follows:

$$\pi_0^{O*} = \frac{8\theta^3 - 16\theta^2 c - 3\theta^2 k + 8\theta c^2 + 6\theta kc + kc^2}{4\theta(8\theta - 3k)} - K(\theta - 1)^2/2$$

$$\pi_t^{O*} = \frac{4c^2 k}{4(8\theta - 3k)^2}$$

Let $\pi_0^{T*}(\theta = 1 + \delta)$, we got a threshold for the cost of product upgrade

$$K^O = \frac{64\theta^2 - 24\theta^2 k - 64\theta c^2 + 9\theta k^2 - 8\theta c^2 k - 24\theta k - 8c^2 k + 3c^2 k^2}{2\theta(\theta - 1)(8\theta - 3k)(8 - 3k)}$$

When $K < K^O$, the manufacturers prefer $\theta = 1 + \delta$, when the manufacturers will invest in the product upgrade in the first stage;Whereas $K > K^O$, the manufacturers will not invest in new product upgrades. All the optimal decisions and profits of the manufacturer and the third-party remanufacturer in Model O are shown in the following table 2:

Table 2 Optimal decision and profit of the third-party remanufacturer for remanufacturing (Model O)

Optimal number of new products: $q_n^{O*} = \frac{2\theta - k + f - 2c}{4\theta - k}$
Optimal quantity of remanufactured products: $q_r^{O*} = \frac{ck + k\theta - 2\theta f}{k(4\theta - k)}$
Optimal licensing fee: $f^* = \frac{8\theta^2 - 3\theta k - ck}{2\theta(8\theta - 3k)k}$
The original product manufacturer's optimal profit: $\pi_0^{O*} = \frac{8\theta^3 - 16\theta^2 c - 3\theta^2 k + 8\theta c^2 + 6\theta kc + kc^2}{4\theta(8\theta - 3k)} - K(\theta - 1)^2/2$
The third party remanufacturer's optimal profit: $\pi_t^{O*} = \frac{4c^2 k}{4(8\theta - 3k)^2}$

The threshold of K: $K^O = \frac{64\theta^2-24\theta^2k-64\theta c^2+9\theta k^2-8\theta c^2k-24\theta k-8c^2k+3c^2k^2}{2\theta(\theta-1)(8\theta-3k)(8-3k)}$

3. Model analysis

3.1 Comparison of optimal quantities

Comparing the optimal production quantities of new products and remanufactured products in Table 1 and Table 2, the following theorem can be obtained:

Theorem 1 When the original product manufacturer engages in its own remanufacturing, the optimal production quantity of new products is always lower than that of outsourcing the remanufacturing business to a third party remanufacturer, i.e.$q_n^{O*} > q_n^{M*}$、$(q_r^{M*} > q_r^{O*})$

Proof: In this case, the optimal production quantity of the new product under model M and Model O is, respectively

$$q_n^{M*} = \frac{\theta - k - c}{2(\theta - k)}$$

$$q_n^{O*} = \frac{8\theta^2 - 8\theta c - 3\theta k + ck}{16\theta^2 - 6k\theta}$$

To prove $q_n^{O*} > q_n^{M*}$, is to prove $q_n^{O*} - q_n^{M*} = \frac{ck(6\theta-k)}{2\theta(8\theta-3k)(\theta-k)} > 0$. For arbitrary , obviously $6\theta - k > 08\theta - 3k > 0$、$\theta - k > 0$, it is easy to get that $q_n^{O*} > q_n^{M*}$

And the optimal production quantities of the remanufactured goods are respectively

$$q_r^{M*} = \frac{\theta - k}{2c}$$

$$q_r^{O*} = \frac{8\theta - 3k}{2c}$$

To prove $q_r^{M*} > q_r^{O*}$, is to prove .For arbitrary $\theta \geq 1 \geq k \geq 0$, it is easy to see that $8\theta - 3k > 0\ and\ \theta - k > 0$. Therefore it always holds $q_r^{M*} > q_r^{O*}$.

In model M all new and remanufactured goods are produced by the original product manufacturer, while in Model O the new goods are produced by the original product manufacturer and the remanufactured goods are outsourced to a third party remanufacturer. Theorem 1 states that when the manufacturer engages in remanufacturing itself, it will produce a larger quantity of remanufactured goods. This is mainly due to two reasons: (1) When the manufacturer undertakes the remanufacturing itself, the classic double marginal effect reappears, which makes it more profitable to remanufacture itself than to outsource the remanufacturing. Therefore, although excessive remanufacturing will erode the market for new products, the manufacturer will still ignore this product erosion phenomenon and supply more remanufactured products to the market. (2) However, if the new product is produced by the original product manufacturer and the remanufactured product is supplied by a third party remanufacturer, the marginal revenue of selling the remanufactured product will be lower than that of selling the new product. Therefore, the manufacturer will produce more new products to compete with the remanufactured products of the third party remanufacturer to reduce the potential product erosion phenomenon.

The explanation for the lower number of new products in Model M than in Model O is as follows: Since outsourcing remanufacturing means that the potential market size for new products in Model M is relatively smaller than in Model O, the original product manufacturer will provide fewer new products when it engages in remanufacturing itself.

3.2 Comparison of product upgrade incentives

By comparing the two thresholds of K in Table 1 and Table 2, we can get the difference of the production upgrade incentive of the original product manufacturer in the first stage when the remanufactured product is produced by the original product manufacturer and the third party remanufacturer respectively, which is summarized as follows.

Theorem 2 When the remanufacturing business is outsourced to the third party remanufacturer, the original product manufacturer always has a higher incentive to upgrade the product, i.e.$K^M < K^O$

Proof: Under models M and O, the scaling coefficients of the product upgrade costs are $K^M = \frac{\theta+k^2-\theta k-k-c^2}{2(\theta-1)(\theta-k)(1-k)}$

$$K^O = \frac{64\theta^2 - 24\theta^2 k - 64\theta c^2 + 9\theta k^2 - 8\theta c^2 k - 24\theta k - 8c^2 k + 3c^2 k^2}{2\theta(\theta-1)(8\theta-3k)(8-3k)}$$

Therefore

$$K^O - K^M = \frac{c^2 k(32\theta^2 k + 32\theta - 36k\theta + 8k - 11k^2 + 3k^3 - 11\theta k^2 + 8k\theta^2}{2\theta(\theta-1)(\theta-k)(k-1)(8\theta-3k)(3k-8)}$$

Since $\theta \geq 1 \geq k \geq 0$, so $32\theta^2 + 32\theta - 36k\theta - 11k^2 - 11\theta k^2 > 0$、$\theta - 1 > 0$、$\theta - k > 0$、$(k-1) < 0$ and $(3k-8) < 0$ are both true. Since both the numerator and the denominator are greater than 0, it can be obtained that is always true.

Theorem 2 shows that manufacturers always have a higher willingness to invest in R&D when they outsource remanufacturing. The explanation is as follows: since the third party remanufacturer is an independent member who will consider maximizing the profit from remanufacturing, the potential product erosion phenomenon cannot be ignored. Facing the competition from third-party remanufacturers' remanufactured products, manufacturer has to invest in product development to improve product quality in order to maximize its own profit, so as to distinguish its upgraded products from remanufactured products and restore its monopoly premium.

The phenomenon revealed in Theorem 2 is known as the "escape from competition" effect [27]. Innovators are more able to avoid the negative impact of competition through further innovation.

3.3 Comparison of economic performance

Theorem 3 Outsourcing remanufacturing to a third party remanufacturer is always bad for the profits of the original product manufacturer, i.e $\pi_0^{O*} < \pi_0^{M*}$

Proof: Under models M and O, the profit of the original product manufacturer is respectively

$$\pi_0^{M*} = \frac{\theta^2 + c^2 + 2\theta c - 2\theta c - \theta k}{4(\theta-k)} - \mathrm{K}(\theta-1)^2/2$$

$$\pi_0^{O*} = \frac{8\theta^3 - 16\theta^2 c - 3\theta^2 k + 8\theta c^2 + 6\theta kc + kc^2}{4\theta(8\theta-3k)} - \mathrm{K}(\theta-1)^2/2$$

Therefore $\pi_0^{M*} - \pi_0^{O*} = \frac{c^2 k(4\theta+k)}{4(\theta-k)\theta(8\theta-3k)}$, since $\theta \geq 1 \geq k \geq 0$、$\theta - k > 0$ and $8\theta - 3k > 0$, so outsourcing remanufacturing to a third party remanu facturer is always bad for the profits of the original product manufacturer, that is $\pi_0^{O*} < \pi_0^{M*}$.

The conventional wisdom is that outsourcing remanufacturing to a third party remanufacturer is generally detrimental to the manufacturer's profit. The reason for this is that in Model M, both new and remanufactured products are produced by the original product manufacturer; In Model O, only the new product is produced by the original product manufacturer, and the remanufactured product is produced by a third party remanufacturer. Therefore, the manufacturer is a monopolist in Model M and faces competition from third-party remanufacturers in Model O. As a result, although the manufacturer produces more new products in Model O, its marginal revenue is also reduced. In addition, the profit from the increased sales of new products is not enough to compensate for the profit erosion caused by the remanufactured products on its new products, so the profit of original product manufacturing is still lower.

3.4 Comparison of environmental sustainability

Life Cycle Assessment (LCA) is often used to measure environmental sustainability and is defined as "compilation and assessment of the input, output and potential environmental impacts of a product system during its entire life", considering the environmental impacts at all stages from raw material procurement to the end of the product life cycle [28-30].

Let e_n, e_u, e_r and represent the environmental impact of a product during sales, use, remanufacturing and disposal respectively. Let and denote the environmental impact of a unit product in sales, use, remanufacturing and disposal, respectively.Because remanufacturing extends the life cycle of new products, the amount of waste disposal is reduced. Therefore, the environmental impact per unit of remanufactured product in waste disposal is smaller than that of new products, i.e. If the total environmental impact of model O(M) is $e^O(e^M)$, the following theorem can be obtained.

Theorem 4 If and only if $\theta > \theta_1$, outsourcing remanufacturing to a third party remanufacturer is better for the environment, i.e. .Otherwise it is better for the environment for the original product manufacturer to engage in remanufacturing itself.

Proof: The total environmental impact of the product during sale, use, remanufacturing and disposal is:

$$e = e_n + e_u + e_r + e_d = i_n q_n + i_u(q_n + q_r) + i_r q_r + i_d q_n$$

The total environmental impact is only related to the optimal production quantity of new/remanufactured goods. Under Model M and Model O, the optimal production quantity of new/remanufactured goods is:

$$q_n^{M*} = \frac{\theta - k - c}{2(\theta - k)}$$

$$q_n^{O*} = \frac{8\theta^2 - 8\theta c - 3\theta k + ck}{16\theta^2 - 6k\theta}$$

$$q_r^{M*} = \frac{\theta - k}{2c}$$

$$q_r^{O*} = \frac{8\theta - 3k}{2c}$$

By substituting the optimal production quantity of new/remanufactured products into the formula of total environmental impact, the total environmental impact under model M and Model O can be obtained as follows:

$$e^O = \frac{8i_n\theta^2 - 8i_n c\theta - 3i_n k\theta + i_n ck + 8i_u\theta^2 - 4i_u c\theta - 3i_u k\theta + i_u ck + 4i_r c\theta + 8i_d\theta^2 - 8i_d c\theta - 3i_d k\theta + i_d ck}{16\theta^2 - 6ku}$$

$$e^M = \frac{i_u\theta - i_n k + i_n\theta - i_n c - i_u k + i_r c - i_d k + i_d\theta - i_d c}{2(\theta - k)}$$

Then $e^M - e^O = \frac{4i_u\theta^2 - 6i_n k\theta - 5i_u k\theta + i_r\theta k - 6i_d k\theta + i_n k^2 + i_u k^2 + 4i_r\theta^2 + i_d k^2}{2c\theta(3k - 8\theta)(\theta - k)} = 0$

Let there be a threshold:

$$\theta_1 = \frac{5i_u + 6i_d + 6i_n + \sqrt{9i_u^2 + 44i_u i_d + 36i_d^2 + 44i_u i_n + 72i_d i_n + i_r^2 + 36i_n^2 - 26i_r i_u - 28i_r i_d - 28i_r i_n)k}}{8(i_u + i_r)}$$

While $\theta > \theta_1$, $e^M - e^O > 0$. it is more beneficial for the environment for the original product manufacturer to engage in remanufacturing himself; $\theta < \theta_1$ $then\ e^M - e^O < 0$, it was better for the environment to outsource remanufacturing to a third party remanufacturer.

Remanufacturing is traditionally thought to save raw materials and therefore be more environmentally friendly, but Theorem 4 shows that this logic misses a key point: in order to obtain more old products for remanufacturing, original product manufacturers may produce new products and remanufactured products of the beam. In particular, when the manufacturer engages in remanufacturing itself, both new and remanufactured products are overproduced, that is $q_n^M + q_r^M > q_n^O + q_r^O$, leading to a greater environmental impact from consumer use of the product in Model M. when $\theta > \theta_1$, these two environmental impacts together exceed the environmental impacts of new product production and disposal, resulting in a greater total environmental impact in Model M than in Model O, i.e $e^M > e^O$

It is worth noting that Theorem 3 shows that the original product manufacturer has a higher benefit from engaging in remanufacturing itself than from outsourcing the remanufacturing business to a third party remanufacturer. This is because the manufacturer then produces a larger quantity of remanufactured goods (known from Theorem 1). Theorem 4, on the other hand, states that overincentives for remanufacturing are not always environmentally beneficial [31].

The inconsistency between the above economic performance and environmental sustainability goals can lead to the loss of managers: if only economic performance is considered, it is better to engage in remanufacturing by yourself than to outsource the remanufacturing business; On the contrary, from the perspective of policy makers, it is better for the environment for enterprises to outsource the remanufacturing business, and there is no need to excessively encourage enterprises to carry out remanufacturing themselves.

3.5 The role of product upgrading

Theorem 5 As the degree of product upgrading increases, the difference in economic performance under Model M and Model O decreases, while the difference in environmental sustainability increases with the degree of product upgrading.

Proof: Under Model M and Model O, the profit of the original product manufacturer is:

$$\pi_0^{M*}=\frac{\theta^2+c^2+2\theta c-2\theta c-\theta k}{4(\theta-k)}-\mathrm{K}(\theta-1)^2/2$$

$$\pi_0^{O*}=\frac{8\theta^3-16\theta^2 c-3\theta^2 k+8\theta c^2+6\theta kc+kc^2}{4\theta(8\theta-3k)}-\mathrm{K}(\theta-1)^2/2$$

Therefore

$$\frac{\partial(\pi_0^{M*}-\pi_0^{O*})}{\partial\theta}=\frac{c^2k(22\theta k^2+20\theta^2 k-64\theta^3-3k^3)}{4(\theta-k)^2\theta^2(8\theta-3k)^2}$$

For any $\theta\geq 1>k>0$, we know that in the numerator, the denominator is greater than 0. So it always holds $\frac{\partial(\pi_0^{M*}-\pi_0^{O*})}{\partial\theta}<0$. That is, when the product upgrade rate increases, the difference in economic performance decreases.

In addition, under Model M and Model O, the proportional coefficients of product upgrade cost are as follows:

$$K^M=\frac{\theta+k^2-\theta k-k-c^2}{2(\theta-1)(\theta-k)(1-k)}$$

$$K^O=\frac{64\theta^2-24\theta^2 k-64\theta c^2+9\theta k^2-8\theta c^2 k-24\theta k-8c^2 k+3c^2 k^2}{2\theta(\theta-1)(8\theta-3k)(8-3k)}$$

Therefore,

$$\frac{\partial(K^O-K^M)}{\partial\theta}=\frac{c^2k\begin{bmatrix}176\theta k^2+160k\theta^2-512\theta^3-24k^3-194\theta k^3-204\theta^2k^2-9k^5\\+128k\theta^3+512\theta^4+18k^5\theta-132k^4\theta^2+338k^3\theta^3+512\theta^5\\-352\theta^4k^2+128k\theta^5+33k^4-128k\theta^4+616k^2\theta^3+86k^3\theta^2\end{bmatrix}}{(\theta-1)^2(\theta-k)^2(1-k)\theta^2(8\theta-3k)^2(3k-8)}$$

For any $\theta\geq 1>k>0$, we know that .$(3k-8)<0$, the remaining terms in the above equation are all greater than 0, so it always holds $\frac{\partial(K^O-K^M)}{\partial\theta}<0$

Finally, under model M and Model O, the total environmental impact is:

$$e^O=\frac{8i_n\theta^2-8i_nc\theta-3i_nk\theta+i_nck+8i_u\theta^2-4i_uc\theta-3i_uk\theta+i_uck+4i_rc\theta+8i_d\theta^2-8i_dc\theta-3i_dk\theta+i_dck}{16\theta^2-6ku}$$

$$e^M=\frac{i_u\theta-i_nk+i_n\theta-i_nc-i_uk+i_rc-i_dk+i_d\theta-i_dc}{2(\theta-k)}$$

Therefore

$$\frac{\partial(e^M-e^O)}{\partial\theta}=\frac{c\begin{bmatrix}32i_u\theta^4+32i_r\theta^4+90i_nk^2\theta^2-96i_n\theta^3k+67i_uk^2\theta^2\\-80i_u\theta^3k-23i_rk^2\theta^2+16i_r\theta^3k+90i_dk^2\theta^2-96i_d\theta^3k\\-22\theta i_nk^3-22\theta i_uk^3-22\theta i_dk^3+3i_nk^4+3i_uk^4+3i_dk^4\end{bmatrix}}{2\theta^2(8\theta-3k)^2(\theta-k)^2}$$

$\theta<\theta_1$, clearly established$\frac{\partial(e^M-e^O)}{\partial\theta}<0$; while $\theta>\theta_1$, $\frac{\partial(e^M-e^O)}{\partial\theta}>0$.

It is worth noting that an increase in product upgrading means that the quality difference between the innovative and the remanufactured product also increases, so the original product manufacturer receives a much larger premium from the innovative product than from the remanufactured product. In addition, Theorem 1 also indicates that when the remanufacturing is outsourced, the manufacturer will produce more new products and less remanufactured products, which will further obtain more premium from the sales of new products. Therefore, both the product upgrading incentive and the difference in economic performance will decrease as the product upgrading degree increases. In addition, since remanufacturing outsourcing leads to higher product upgrading incentives, the difference in environmental sustainability increases with the increase of product upgrading degree.

4. Conclusion

Interest in sustainability in the global business community has increased dramatically in recent years, and many original product manufacturers have come to view remanufacturing as an integral part of their business models. Despite the profitability of remanufacturing, consumers often perceive remanufactured products to be less valuable than new products, and many consumers even associate cheap remanufactured products with the manufacturer's brand, tarnish its brand image. As a result, many manufacturers no longer do remanufacturing themselves, but outsource the remanufacturing to third parties. It is important to point out that remanufactured goods will eat into the market share of new products, regardless of whether the remanufacturing business is done by the original product manufacturer or outsourced to a third party remanufacturer. To this end, many manufacturers introduce upgradable product strategies to differentiate the upgradable product from the remanufactured product at the maximum quality level, thus mitigating the potential product erosion problem.

This paper focuses on the analysis of the optimal decision of manufacturer to engage in new product upgrade R&D under two different scenarios: manufacturer engaged in remanufacturing or outsourcing its remanufacturing business to an independent third party remanufacturer. This paper discusses the optimal upgrading strategy of manufacturers in the case that manufacturers both produce new products and recycle and remanufacture discarded products (Model M). Specifically, the manufacturer decides whether to invest in product upgrading in the first stage, determines the optimal production quantity of new products and remanufactured products in the second stage, and solves the optimal decision of the manufacturer by using the first-order condition. Then, in the case that the manufacturer produces new products and outsources the remanufacturing business to an independent third party remanufacturer (Model O), the optimal upgrading strategy of the manufacturer is discussed.

In the first stage, the manufacturer still decides whether to invest in the product upgrade, but in the second stage, the manufacturer first determines the remanufacturing license fee to the third party remanufacturer, and then it and the third party remanufacturer simultaneously decide the optimal production quantity of new products and remanufactured products. By constructing a game model, the optimal output, the optimal price and the product upgrading strategy of the manufacturer and the third-party remanufacturer are solved by backward induction. Then we compare the difference of equilibrium outcomes between the two scenarios. The results show that: (1) the optimal number of new products when the original product manufacturer engages in remanufacturing is always lower than the optimal number of new products when the remanufacturing business is outsourced to a third party remanufacturer; On the contrary, the optimal quantity of remanufactured products when the manufacturer engages in remanufacturing by itself is always higher than the optimal quantity of remanufactured products when the manufacturer outsources the remanufacturing to the third-party remanufacturer. (2) The impact of the interaction of the above optimal decisions on the manufacturers' product upgrade incentives is as follows: when the manufacturers outsource the remanufacturing to a third party remanufacturer, the manufacturers always have higher incentives to upgrade products; (3) The effects of the interaction of the above optimal decisions on the economic performance and environmental sustainability of the manufacturers and the third party remanufacturers are as follows: outsourcing the remanufacturing business to the third party remanufacturers is always detrimental to the manufacturers' profits; (4) Only when the quality difference between the general new product and the upgraded product is greater than a threshold, outsourcing the remanufacturing business to the third party remanufacturer is better for the environment. (5) The role of manufacturer's product upgrade decision in the whole game is as follows: the difference in product upgrade incentive and economic performance between manufacturer engaged in remanufacturing and outsourcing remanufacturing business decreases with the increase of product upgrade degree; The difference of environmental sustainability increases with the increase of product upgrading degree.

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