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How Does Licensing Remanufacturing Affect the Supply Chain Considering Customer Environmental Awareness?

Zongbao Zou, Fan Wang, Xiaofan Lai * and Jingxian Hong

Sun Yat-sen Business School, Sun Yat-sen University, Guangzhou 510275, China; zzbkr123@163.com (Z.Z.); fanwang@gmail.com (F.W.); hongjx5@mail2.sysu.edu.cn (J.H.)

* Correspondence: xiaofanlai@gmail.com; Tel.: +86-20-8411-1659

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Abstract: As sustainability issues are receiving increasing attention in society, in recent years many manufacturers have been adopting remanufacturing via technology licensing. This paper uses a game theory approach to investigate this strategy of a manufacturer under a closed-loop supply chain consisting of one supplier, one manufacturer, and one third-party remanufacturer (TPR), with the consideration of customer environmental awareness. In particular, the supplier supplies the components to the manufacturer and the manufacturer adopts technology licensing remanufacturing via the TPR. We explicitly characterize the reactions between the supplier and the manufacturer as being in equilibrium after adopting the technology licensing. We find that only when remanufacturing is a potential threat to the supplier is the performance of the supply chain improved and the double marginalization effect effectively eliminated. Moreover, remanufacturing by technology licensing only increases the profit of the manufacturer, but decreases the profit of the supplier. Interestingly, contrary to traditional wisdom, the existence of remanufactured products does not reduce the quantity of new products. Furthermore, remanufacturing by technology licensing may not always improve the environment, but customers in the market have environmental awareness that facilitates remanufacturing.

Keywords: technology licensing remanufacturing; third-party remanufacturer; customer environmental awareness

1. Introduction

The growing shortage of natural resources and the deterioration of human living environments have prompted many countries and regions to make great efforts to improve environment management ability and resource utilization efficiency. As a production strategy offering all-round sustainability, remanufacturing is encouraged [1] because it has several advantages that help with maintaining environmental sustainability. On the one hand, remanufacturing reuses some parts from end-of-life (EOL) products, and hence the production cost of the remanufactured products is always lower than that of brand-new products [2,3]. On the other hand, remanufacturing consumes fewer raw materials and less energy than manufacturing new products. Moreover, it reduces carbon emissions and diverts EOL products from landfills. In practice, many famous firms have gained rich economic benefits by carrying out remanufacturing, and simultaneously improved their environmental protection profile. For example, in 2007, Caterpillar's remanufacturing division, one of its fastest-growing divisions, generated $2 billion in sales. IBM made billions of dollars in revenue by collecting and remarketing millions of units of used IT equipment [4].

However, most manufacturers do not perform the remanufacturing themselves but by cooperating with a third-party remanufacturer (TPR), which is called *technology licensing*. Technology licensing is an official permission or permit that means that the licensor (e.g., the manufacturer in our study) provides the technology to the licensee (e.g., the TPR) to use rather than transferring the ownership, and the latter should pay the former a royalty rate according to an agreement reached by them [5]. The reason for this phenomenon is that not all manufacturers can perform remanufacturing functions in a profitable way [1,4]. According to a database of over 2000 remanufacturing firms in the USA, only 6% of them are manufacturers [6,7]. Therefore, technology licensing has been increasingly employed by manufacturers around the world in carrying out remanufacturing operations [8]. For example, Cat Reman provides remanufacturing services for many major manufacturers, such as Perkins, Alcoa, Ford, and Honeywell. Xin Meifu, the largest automobile gearbox remanufacturer in China, acts as a remanufacturing service provider for ZF Friedrichshafen AG and Aisin, the two largest gearbox manufacturers in the world [9]. For more examples of the licensing remanufacturing see the list in Table 1, which implies that licensing remanufacturing is an important form of remanufacturing in China [10]. Unfortunately, while both manufacturers and TPRs reap the benefits of remanufacturing through technology licensing, the suppliers get a raw deal because they may be not able to gain any profit from the remanufactured products. Facing this threat, suppliers will strategically adjust their decisions, which will in turn influence the decisions of the manufacturers [11].

Table 1. List of surveyed remanufacturing companies in China (see Zhang et al. [10]).

Remanufacturing Company	Form	Remanufactured Product
Weichai Power Remanufacturing Co. Ltd.	Manufacturers	Diesel engine
Jinan Diesel Engine Co. Ltd.	Manufacturers	Diesel engine
Shanghai Diesel Engine Remanufacturing Co. Ltd.	Licensing Remanufacturing	Diesel engine
Yuchai Remanufacturing Services (Suzhou) Co. Ltd.	Manufacturers	Diesel engine
Wuxi Dahao Power Co. Ltd.	Manufacturers	Diesel engine
Shanghai Xingfu Rebuild Power train Co. Ltd.	Licensing Remanufacturing	Gasoline engine
Zhangjiagang Furui Special Equipment Co. Ltd.	Independent Remanufacturing	LNG engine
Shanghai Xinfumei Transmission Technology Service Co. Ltd.	Independent Remanufacturing	Automatic transmission
PICO (Changshu) Auto Motor Remanufacturer	Independent Remanufacturing	Starter, Alternator
Shanghai Bentuo Turbocharger System Co. Ltd.	Licensing Remanufacturing	Turbocharger
Caterpillar Remanufacturing Service (Shanghai) Co. Ltd.	Manufacturers	Fuel pump, Cylinder Cover, etc.
Kangyue Technology Co. Ltd.	Manufacturers	Turbocharger

Meanwhile, growing concerns over environmental protection, especially concerns from the customers, have created important incentives for companies to seriously consider the remanufacturing operation [12]. That is, customer environmental awareness plays an important role in the operational decisions and the environmental impact, because the environmental awareness of the customers may affect their choices about different types of products, and in turn affect other decisions in the supply chain.

Motivated by the above facts, in this paper, we consider the interaction between the manufacturer and the supplier when the manufacturer signs technology licensing remanufacturing agreements with a TPR, with the consideration of environmental awareness of the customers. More specifically, we focus on the following research questions:

(1) From the supply chain perspective, should the supplier raise or reduce the wholesale price when his downstream manufacturer develops technology licensing remanufacturing via a TPR? In turn, how does the manufacturer adjust his quantity of orders from the supplier?
(2) From an environmental perspective, how does customer environmental awareness affect the decisions, and what impact does the remanufacturing have on the environment?

In order to answer these questions, we build game theory models to characterize the relationship between the three parties, namely, one supplier, one manufacturer, and one TPR. We compare the equilibrium results under technology licensing remanufacturing operations with those under no technology licensing remanufacturing operation. Moreover, we conduct an environmental analysis to find out how customer environmental awareness affects the decisions of the supply chain, and investigate what impacts the remanufacturing has on the environment.

To the best of our knowledge, this is the first study concerning licensing remanufacturing with the consideration of customer environmental awareness. We find that only when remanufacturing is a potential threat to the supplier is the performance of the supply chain improved and the double marginalization effect effectively eliminated. Moreover, we find that remanufacturing by technology licensing only increases the profit of the manufacturer, but reduces the profit of the supplier. Interestingly, contrary to traditional wisdom, the existence of remanufactured products does not reduce the quantity of new products. Specifically, we have found out that in certain scenarios, the manufacturer may order more new products from the supplier when the manufacturer develops technology licensing remanufacturing. Furthermore, remanufacturing by technology licensing may not always make the environment better, although customers in the market have environmental awareness that facilitates remanufacturing.

The remainder of this paper is organized as follows. We review the related literature in the next section. In Section 3, we present both the models with and without technology licensing remanufacturing and obtain their equilibrium results, respectively. Based on the equilibrium results, we make a comparative analysis in Section 4. Section 5 presents the environment-related analysis, which is followed by conclusions and future research in Section 6. All the proofs are placed in Appendix A.

2. Literature Review

This paper is closely related to three streams of research in the literature: research on technology licensing remanufacturing; research on sustainability issues in supply chain management, such as environmental laws and legislations, carbon policy, and sustainability investment; and research on sustainability aspects under the cooperative supply chain.

The technology licensing remanufacturing has received extensive attention in the recent operational management literature (e.g., Zou et al. [3], Huang and Wang [5], Hong et al. [7], Huang and Wang [8], Ma et al. [9], Hashiguchi [13], Oraiopoulos et al. [14], Abdulrahman et al. [15], and Niu and Zou [16]). In particular, Hashiguchi [13] summarized cases in Japan and USA of conflicts in third-party remanufacturing between TPRs and manufacturers, and suggested that TPRs should purchase licenses from manufacturers so as to avoid such conflicts. Oraiopoulos et al. [14] introduced a widely employed technology licensing form under a closed-loop supply chain of IT industry, where the manufacturers charge license fees from customers who bought remanufactured products, instead of from third-party remanufacturers, as mentioned before. Hong et al. [7] mainly compared two different licensing forms, i.e., a fixed technology fee and a loyalty rate, and found that the former dominates from the perspective of the customer surplus and environment impacts. Huang and Wang [8] analyzed the effects of different players carrying out remanufacturing operations on information sharing between the distributor and the manufacturer. They suggested that developing licensing remanufacturing can effectively suppress the negative effect of information sharing on the retailer. Niu and Zou [16] discussed the incentives of investment in big data technology in a licensed remanufacturing supply chain, and the effects information sharing and risk attitude have on the environmental impact. Compared to the works above, our paper contributes in that the reaction of the supplier in the manufacturer's decision on technology licensing remanufacturing is explored. More importantly, we also take the customer environmental awareness into consideration and discuss what impacts that awareness has on the environment.

Sustainability issues have been attracting widespread attention and been investigated extensively due to their significant impacts on human society. Previous research analyzed these issues covering an impressive variety of streams of research in supply chain management literature. For example, many works studied the effects of environment laws and legislations on operational decisions, such as electronic equipment waste and extended producer responsibility (e.g., Toyasaki et al. [17], Hammond and Beullens [18], Atasu and Van Wassenhove [19], Atasu and Subramanian [20], Jacobs and Subramanian [21]). Moreover, there are some papers examining how carbon trading, carbon constraints, or carbon tax can affect the decisions of the members in the supply chain. For example, Dobos [22] studied the effect of carbon trading on production and inventory decisions. Choi [23] pointed out that a carbon tax scheme can induce fashion retailers to join the quick response system. Shen et al. [24], based on low-carbon practices in the textile industry in China, examined how the energy consumption constraint influences members to adjust their operational decisions. Some other work has investigated sustainability investment decisions in a supply chain. For example, Dong et al. [25] studied the sustainability investment considering the cap-and-trade regulation, and pointed out that operational decisions are greatly affected by sustainability investment efficiency. Shi et al. [26,27] examined how the power structure affects sustainability investment efficiency, and found that the partner with less power in a supply chain has more incentives to invest sustainably. Although those studies focus on sustainability issues, our paper is different in that we mainly discuss how the environment is affected under a setting of remanufacturing, and in such settings we also consider the environmental awareness in the customer choice model.

Literature on sustainability issues in the cooperative supply chain is also related to our paper. For example, Sinayi and Rasti-Barzoki [28] studied the effect of government intervention on the profits of the supply chain members, greening level of the product, and consumer surplus, and found that cooperation between members always results in greener products, more profit in the supply chain, and a higher consumer surplus. Hong and Guo [29] considered three different cooperation-level contracts, and pointed out that cooperation can improve the environmental performance but is not always profitable for all the members in the supply chain. Banyai [30] showed that the cooperation among package service providers may increase energy efficiency in a real-time decision-making model of first mile and last mile logistics. Those papers mainly focus on how the cooperation between the supply chain members affects the environment, but our paper is concerned about how remanufacturing and customer environmental awareness affect the environment.

Table 2 shows the positioning of our paper in the literature. As shown in Table 2, our paper is the first study concerning the sustainability issues that contain the licensing remanufacturing and customer environmental awareness.

Table 2. The positioning of this paper in the literature.

Papers\Issues	Environmental Impact (Sustainability)	Customer Choice Behavior	Customer Environmental Awareness	Licensing	Other Types of Remanufacturing
Choi [23], Shen et al. [24], Shi et al. [27], Sinayi and Rasti-Barzoki [28], Banyai [30]	√				
Toyasaki et al. [17], Hammond and Beullens [18], Atasu and Subramanian [20]					√
Huang and Wang [5], Huang and Wang [8], Hashiguchi [13], Oraiopoulos et al. [14]				√	√
Atasu and Van Wassenhove [19], Jacobs and Subramanian [21]	√				√
Dong et al. [25], Shi et al. [26]	√		√		
Dobos [22]	√			√	
Hong and Guo [29]	√	√	√		
Hong et al. [7], Ma et al. [9]		√		√	√
Zou et al. [3], Niu and Zou [16]	√	√		√	√
This paper	√	√	√	√	√

3. Models and Equilibrium Results

In this section, we first provide a model description, and then present two models, a no-remanufacturing model (model NR) and a licensing remanufacturing model (model LR), as well as their equilibrium results. The first model does not contain remanufacturing and serves as the benchmark so as to emphasize the effect of remanufacturing on the decisions of supply chain members in the second model.

3.1. Model Description

3.1.1. A Closed-Loop Supply Chain

This paper focuses on a closed-loop supply chain consisting of one supplier, one manufacturer, and one TPR. The supplier provides the components to the manufacturer, who produces the new products to the market. The manufacturer may choose to adopt technology licensing remanufacturing, as mentioned before. If adopting, the manufacturer licenses the TPR to recycle the EOL products, produce remanufactured products, and sell those to the same market. In the market, some customers have environmental awareness that may affect their choices on different types of products. Our study addresses the problem of how the introduction of licensing remanufacturing affects the operational decisions of the players in this supply chain, where the customers have environmental awareness. The setting of the closed-loop supply chain with licensing remanufacturing is shown in Figure 1.

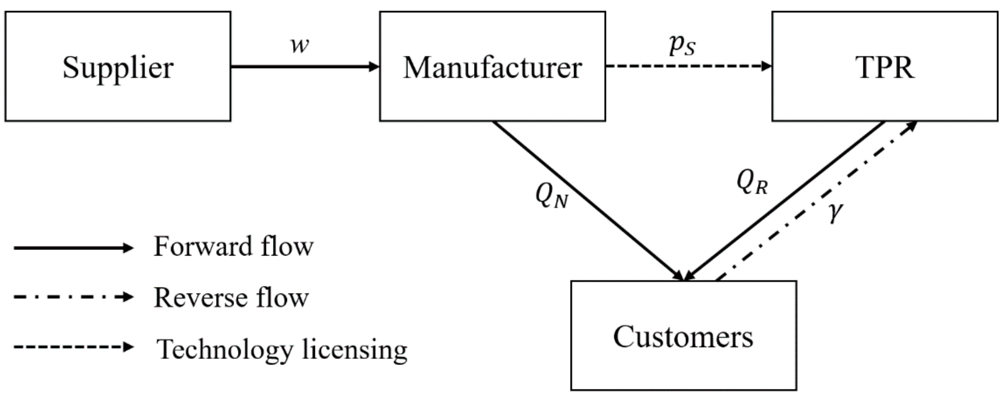

Figure 1. Closed-loop supply chain.

We consider a theoretical-game model for the problem. At the beginning of the game, the supplier sets the wholesale price w for the components. Then, given the wholesale price of the components, the manufacturer sets the production quantity Q_N of new products, and the technology license fee p_S for remanufacturing if the manufacturer adopts the licensing remanufacturing via a TPR. Finally, the TPR sets the return price γ of EOL products and the quantity Q_R of the remanufactured products. The timeline of events is plotted in Figure 2. Clearly, in the model NR, the manufacturer does not need to set the license fee and there are no TRP decisions.

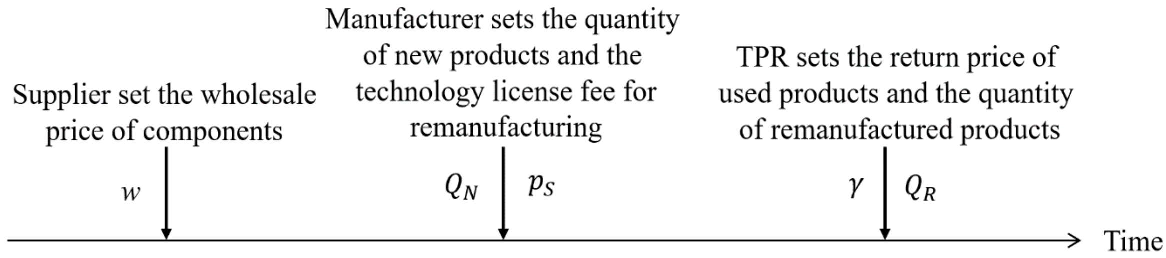

Figure 2. Timeline of events.

3.1.2. Customer Choice Behavior with Environmental Awareness

In our model, we take the customer environmental awareness into account when considering customer choice behavior (Oraiopoulos et al. [14]), and we assume that the potential market size is normalized to be one in each model. There are two types of product in the market, namely, the new product from the manufacturer and the remanufactured product from the TRP. We denote a customer's willingness to pay for a new product as v, which is assumed to be distributed uniformly over [0, 1]. A customer with willingness to pay v for a new product has a willingness to pay δv for a remanufactured product, where $\delta \in (0, 1)$ reflects the consumer's value discount for remanufactured products, and also shows the substitutability of remanufactured products versus new products. In the rest of the paper, we use these two concepts alternatively. Let the prices of the new and remanufactured products be p_N and p_R, respectively. Then a customer with willingness to pay v obtains the net utility $U_N = v - p_N$ from purchasing a new product, and derives the net utility $U_R = \delta v - p_R + g$ from buying a remanufactured unit, where g represents the customer environmental awareness of the remanufactured product. A bigger value g represents higher customer environmental awareness. Obviously, as long as $v \geq p_N$, the customer with willingness to pay v finds the new product acceptable, and as long as $v \geq (p_R - g)/\delta$, the customer finds the remanufactured product acceptable. Therefore, if only new products are sold in the market, a customer with willingness to pay $v \geq p_N$ will buy the new product. However, when both new and remanufactured products are sold simultaneously, the customer will buy the new product (remanufactured product) if and only if his corresponding utility is positive and is larger than his utility from buying the remanufactured product (new product); therefore, we have

- a customer with willingness to pay $v - p_N \geq \max(\delta v - p_R + g, 0)$ will buy the new product;
- a customer with willingness to pay $\delta v - p_R + g \geq \max(v - p_N, 0)$ will buy the remanufactured product;
- and a customer with willingness to pay $v - p_N < 0$ and $\delta v - p_R + g < 0$ will buy nothing.

3.1.3. Demand Functions

Based on the above analysis, we can derive the demand functions of the new and remanufactured products. In model NR, since there are no remanufactured products, customers with willingness to pay $v \in [p_N, 1]$ will buy the products. In the model LR, there are both new products and remanufactured products, so customers with willingness to pay $v \in [(p_N - p_R + g)/(1-\delta), 1]$ prefer to buy the new products and customers with willingness to pay $v \in [(p_R - g)/\delta, (p_N - p_R + g)/(1-\delta))$ will buy the remanufactured products. Since v is distributed uniformly over [0, 1], the demand of the new products in model NR is

$$Q_{\text{N-NR}} = \int_{p_N}^{1} f(v)dv = 1 - p_N \tag{1}$$

and the demands of the new products and remanufactured products in model LR are

$$Q_{\text{N-LR}} = \int_{(p_N - p_R + g)/(1-\delta)}^{1} f(v)dv = 1 - \frac{p_N - p_R + g}{1-\delta} \tag{2}$$

$$Q_{\text{R-LR}} = \int_{(p_R - g)/\delta}^{(p_N - p_R + g)/(1-\delta)} f(v)dv = \frac{p_N - p_R + g}{1-\delta} - \frac{p_R - g}{\delta}, \tag{3}$$

where $f(v)$ is the probability density function of v. They lead to the inverse demand functions via simple algebraic operations as follows:

$$p_N = 1 - Q_N - \delta Q_R \tag{4}$$

$$p_R = \delta(1 - Q_N - Q_R) + g. \tag{5}$$

3.1.4. Return Function

After getting the license for remanufacturing, the TPR recycles the EOL products with a certain return price. We assume the collecting quantity of EOL products is linear increasing function with respective to return price γ,

$$Q_T = \alpha + \beta\gamma. \tag{6}$$

Here, the value of α means the collecting amount when the return price $\gamma = 0$. β represents the sensitivity of the customers to the return price. This kind of return function is common in the literature, such as Bakal and Akcali [31]. For tractability, we assume all recycled products can be used for remanufacturing. Therefore, the optimal return quantity of remanufactured products equals the demand for the remanufactured products.

3.1.5. Production Cost

Since the remanufactured products reuse some components from the EOL products, the production cost of the remanufactured product is always less than that of the new product. Generally, firms can save 40–65% of production costs through remanufacturing (Savaskan et al. [32]). Therefore, we denote the production costs of the new product and remanufactured product as c_N and c_R, respectively, with $c_N \geq c_R$.

3.2. Models and Equilibrium Results

As mentioned before, we aim to investigate how the licensing remanufacturing will affect the decisions in the supply chain; therefore, we start in this subsection by providing a model with no remanufacturing, namely model NR, which acts as a benchmark for us to compare the equilibrium results with those of the model with remanufacturing (model LR).

3.2.1. No-Remanufacturing Model (Model NR)

For the model NR, there are only two players in the supply chain, i.e., the supplier and the manufacturer, where the manufacturer does not need to set the license fee and there are no TRP decisions. In this setting, the supplier's and the manufacturer's decision problems are as follows, respectively:

$$\max_{w} \Pi_{\text{S-NR}} = (w - c_N)Q_N \tag{7}$$

$$\max_{Q_N} \Pi_{\text{M-NR}} = (1 - Q_N - w)Q_N. \tag{8}$$

By solving these two problems, the equilibrium outcomes of model NR can be summarized by the following lemma.

Lemma 1. *In model NR, the equilibrium wholesale price and the equilibrium quantity of the new products are* $w = \frac{1+c_N}{2}$ *and* $Q_N = \frac{1-c_N}{4}$*, respectively; and the equilibrium profits of the supplier and manufacturer are* $\Pi_{\text{S-NR}} = \frac{(1-c_N)^2}{8}$ *and* $\Pi_{\text{M-NR}} = \frac{(1-c_N)^2}{16}$*, respectively.*

The results of Lemma 1 provide a benchmark for comparing the results after the manufacturer adopts the licensing remanufacturing via a TRP.

3.2.2. Licensing Remanufacturing Model (Model LR)

Now we consider the case that the manufacturer develops remanufacturing operations via technology licensing. Therefore, as shown in the Figure 1, there are three players in the close-loop supply chain, namely, the supplier, the manufacturer and the TPR. Their decision problems are as follows, respectively:

$$\max_{w} \Pi_{\text{S-LR}} = (w - c_N)Q_N \tag{9}$$

$$\max_{Q_N, p_S} \Pi_{\text{M-LR}} = (p_N - w)Q_N + p_S Q_R \tag{10}$$

$$\begin{aligned} &\max_{Q_R, \gamma} \Pi_{\text{TPR-LR}} = (p_R - c_R - p_S)Q_R - \gamma Q_T \\ &\text{s.t. } 0 \le Q_R \le Q_N,\ Q_T \le Q_N \end{aligned} \tag{11}$$

The sequence of the game is as follows. First, the supplier sets the wholesale price of the components for new products. Then, given the wholesale price of the supplier, the manufacturer decides the production quantity of the new products, and decides whether or not to develop the technology licensing remanufacturing. If adopting the technology licensing, the manufacturer should also set the licensing fee. Finally, the TPR decides the return price of the EOL products and the quantity of remanufactured products. Following this sequence, we use backward induction to solve this game in the following.

Decisions of the TPR

Given the manufacturer's decision variables Q_N and p_S, we now discuss the TPR's decision on Q_R and γ. Since we do not consider demand uncertainty on both the remanufactured products and the return quantity of the EOL products, the TPR has no incentive to collect more EOL products than the quantity of remanufactured products, i.e., we have $Q_R = Q_T$. Therefore, by simple handling the expressions of Q_R and γ, it is easy to show that the return price γ satisfies the following Lemma 2.

Lemma 2. *Given the price of new product and remanufactured product, i.e.,* p_N *and* p_R*, the optimal return price of EOL product is* $\gamma = \frac{\delta p_N - p_R + g - \alpha\delta(1-\delta)}{\delta\beta(1-\delta)}$.

Substituting the result of Lemma 2 into (11), the TPR's decision problem can be rewritten as

$$\begin{aligned} &\max_{Q_R} \Pi_{\text{TPR-LR}} = \left(\delta(1 - Q_N - Q_R) + g - c_R - p_S - \tfrac{Q_R - \alpha}{\beta}\right)Q_R \\ &\text{s.t. } 0 \le Q_R \le Q_N. \end{aligned} \tag{12}$$

Similar to Atasu et al. [12] and Wang et al. [33], for ease of handling, we do not consider the constraint $Q_N \ge Q_R$ in the following text. In order to avoid unrealistic situations, we assume $c_N \le 1 - \frac{(4+2\delta+4\delta\beta+\delta^2\beta)(\delta\beta+\beta g-\beta c_r+\alpha)}{2(2+5\delta\beta+3\delta^2\beta^2)}$. In the following proposition, the best response remanufacturing quantity function of the TPR is given.

Proposition 1. *Given* Q_N *and* p_S*, the TPR's optimal remanufacturing quantity is*

$$Q_{\text{R-LR}} = \begin{cases} \frac{\delta\beta(1-Q_N) - \beta(c_R + p_S - g) + \alpha}{2(1+\delta\beta)}, & \text{if } \frac{\delta\beta(1-Q_N) - \beta(c_R - g) + \alpha}{\beta} \ge p_S \\ 0, & \text{if } \frac{\delta\beta(1-Q_N) - \beta(c_R - g) + \alpha}{\beta} < p_S \end{cases}. \tag{13}$$

Corollary 1. *When TPR undertakes remanufacturing, the quantity of the remanufactured product decreases monotonously in the quantity of new product, the decreasing rate is positively related to δ, the substitutability of remanufactured product for new product.*

Corollary 1 shows that the competition intensity is determined by the substitutability of the remanufactured product for the new product. The increase in the quantity of one product would reduce the sale quantity of the other product.

Decisions of the Manufacturer

By substituting the best response quantity function in Equation (13) into Equation (10), we can rewrite the manufacturer's decision problem. Based on a piecewise function of the best response function Q_R with respect to Q_N and p_S, we discuss the manufacturer's problem in the following two cases.

- Case 1: When $[\delta\beta(1-Q_N)-\beta(c_R-g)+\alpha]/\beta \geq p_S$, TPR carries out remanufacturing, given the wholesale price of the supplier, the corresponding manufacturer's decision problem is as follows:

$$\begin{aligned} \max_{Q_N, p_S} \Pi_{M-LR} &= (1-Q_N-w)Q_N + \frac{(p_S-\delta Q_N)[\delta\beta(1-Q_N)-\beta(c_R+p_S-g)+\alpha]}{2(1+\delta\beta)} \\ \text{s.t. } & \frac{\delta\beta(1-Q_N)-\beta(c_R-g)+\alpha}{\beta} \geq p_S. \end{aligned} \tag{14}$$

- Case 2: When $[\delta\beta(1-Q_N)-\beta(c_R-g)+\alpha]/\beta < p_S$, TPR does not have any incentives to undertake remanufacturing, therefore, given the wholesale price of the supplier, the manufacturer's decision problem becomes

$$\begin{aligned} \max_{Q_N, p_S} \Pi_{M-LR} &= (1-Q_N-w)Q_N \\ \text{s.t. } & \frac{\delta\beta(1-Q_N)-\beta(c_R-g)+\alpha}{\beta} < p_S. \end{aligned} \tag{15}$$

Solving the above two constrained nonlinear programming problems yields Proposition 2.

Proposition 2. *When the manufacturer licenses the TPR to remanufacture, given the wholesale price of the supplier w, the manufacturer's optimal decisions on product quantity and price are as follows, respectively:*

$$Q_{N-LR} = \begin{cases} \frac{1-w}{4}, & \text{if } w \leq \frac{\beta(c_R-g)-\alpha}{\delta\beta} \\ \frac{2(1+\delta\beta)(1-w)-\delta[\delta\beta-\beta(c_R-g)+\alpha]}{2(2+2\delta\beta-\delta^2\beta)}, & \text{if } w > \frac{\beta(c_R-g)-\alpha}{\delta\beta} \end{cases} \tag{16}$$

$$p_S = \begin{cases} \max\left\{\frac{\delta\beta(1+w)-2\beta(c_R-g)+2\alpha}{2\beta}, 0\right\}, & \text{if } w \leq \frac{\beta(c_R-g)-\alpha}{\delta\beta} \\ \frac{\delta\beta-\beta(c_R-g)+\alpha}{2\beta}, & \text{if } w > \frac{\beta(c_R-g)-\alpha}{\delta\beta} \end{cases}. \tag{17}$$

Corollary 2. *New product quantity is decreasing in wholesale price w, and the decreasing rate is higher under the remanufacturing case than without remanufacturing.*

To interpret the results, note that the manufacturer's revenue is determined by two factors, the sales of new products, and the technology license fee charged by TPR. The trade-off for the manufacturer is the profit generated from technology licensing remanufacturing and the cannibalization of new products from remanufactured products. The TPR entering into the market would reduce customer demand for new products, which in turn harms the supplier. Therefore, the supplier would adopt a strategic wholesale price to fight the competition from remanufactured products.

Decisions of the Supplier

Substituting the quantity of the new product in Equation (16) into the objective function (Equation (9)) yields the problem of the supplier under different situations. Similar to the manufacturer's decision problem, we discuss the supplier's decision problem in the two cases as follows:

- Case 1: When the TPR recycles EOL products and undertakes remanufacturing, the supplier's decision problem is

$$\begin{array}{c} \max\limits_{w} \Pi_{\mathrm{S-LR}} = \frac{(w-c_{\mathrm{N}})\{2(1+\delta\beta)(1-w)-\delta[\delta\beta-\beta(c_{\mathrm{R}}-g)+\alpha]\}}{2(2+2\delta\beta-\delta^2\beta)} \\ \text{s.t. } \frac{\beta(c_{\mathrm{R}}-g)-\alpha}{\delta\beta} \le w. \end{array} \tag{18}$$

- Case 2: When the TPR does not remanufacture, the supplier's decision problem is

$$\begin{array}{c} \max\limits_{w} \Pi_{\mathrm{S-LR}} = \frac{(w-c_{\mathrm{N}})(1-w)}{2} \\ \text{s.t. } w < \frac{\beta(c_{\mathrm{R}}-g)-\alpha}{\delta\beta} \end{array} \tag{19}$$

Solving the above two constrained nonlinear programming problems yields the following Proposition 3.

Proposition 3. *The optimal wholesale price for the supplier is*

$$w_{\mathrm{S}} = \begin{cases} \frac{1+c_{\mathrm{N}}}{2}, & \text{if } 0 \le c_{\mathrm{N}} < \max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \\ \frac{\beta(c_{\mathrm{R}}-g)-\alpha}{\delta\beta}, & \text{if } \max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_{\mathrm{N}} < c_{\mathrm{N}}' \\ \frac{1+c_{\mathrm{N}}}{2} - \frac{\delta[\delta\beta-\beta(c_{\mathrm{R}}-g)+\alpha]}{4(1+\delta\beta)}, & \text{if } c_{\mathrm{N}}' \le c_{\mathrm{N}}, \end{cases} \tag{20}$$

where $c_{\mathrm{N}}' = \frac{(4+4\delta\beta-\delta^2\beta)[\beta(c_{\mathrm{R}}-g)-\alpha]-\delta\beta(2+2\delta\beta-\delta^2\beta)}{2\delta\beta(1+\delta\beta)}$.

Corollary 3. *In model LR, the supplier always reduces the wholesale price to induce the manufacturer to abandon technology licensing remanufacturing.*

By Proposition 3 and from Figure 3, when $\max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_{\mathrm{N}} < c_{\mathrm{N}}'$, the reduction of the wholesale price is $\frac{1}{2} + \max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{2\delta\beta}, 0\right\} - \frac{\beta(c_{\mathrm{R}}-g)-\alpha}{\delta\beta} \ge 0$. In this setting, the supplier induces the manufacturer to abandon technology licensing remanufacturing. However, when $c_{\mathrm{N}}' \le c_{\mathrm{N}}$, the supplier reduces the wholesale price by $\frac{\delta[\delta\beta-\beta(c_{\mathrm{R}}-g)+\alpha]}{4(1+\delta\beta)}$ in model LR compared with the wholesale price $w = \frac{1+c_{\mathrm{N}}}{2}$ in model NR, in order to induce the manufacturer to increase the order quantity of the components for the productions of the new products.

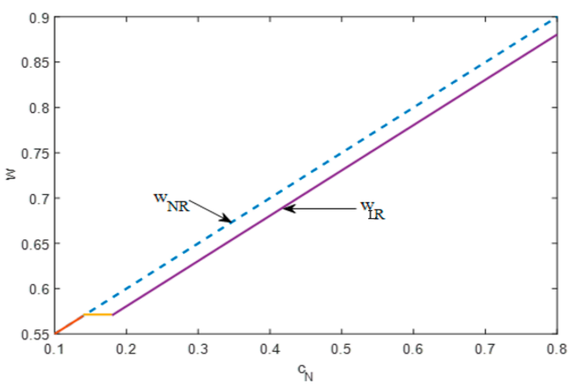

Figure 3. The optimal wholesale prices of the supplier in model NR and model LR.

4. Equilibrium Analysis

In this section, we first analyze the equilibrium results in model LR, and then compare the results between model LR and model NR, so as to highlight the effect of technology licensing remanufacturing on the decisions of the supplier and the manufacturer.

Firstly, we provide Figure 4 to graphically depict the equilibrium regions in model LR. In particular, there are a total of three regions in Figure 4, namely regions VNR, FNR, and R. Region VNR represents a scenario in which the manufacturer voluntarily abandons technology licensing remanufacturing operations; region FNR represents a scenario in which the supplier reduces the wholesale price to force the manufacturer to abandon technology licensing remanufacturing operations; region R represents a scenario in which the manufacturer develops technology licensing remanufacturing. In region VNR, since the perceived value of remanufactured products for the customers is low, the manufacturer has no incentive to develop technology licensing remanufacturing, even though the supplier sets a high wholesale price $(1 + c_N)/2$. In region FNR, only when the supplier reduces the wholesale price, the manufacturer will abandon technology licensing remanufacturing. For cases where the customers perceive a high value of the remanufactured product, as shown in region R of Figure 4, although the supplier reduces the wholesale price, the manufacturer still adopts the technology licensing remanufacturing.

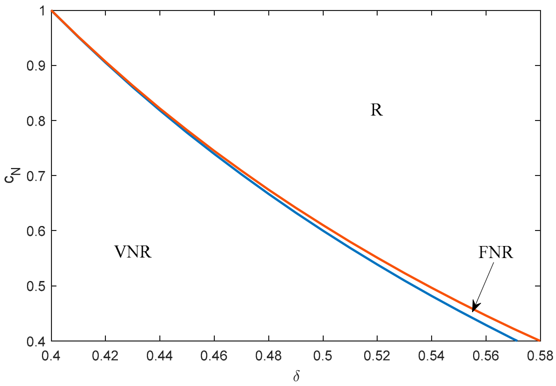

Figure 4. The equilibrium regions in model LR ($c_R = 0.4$, $\alpha = 0$, $g = 0$).

Recall that Proposition 3 provides the equilibrium wholesale price of the supplier. By substituting that into Proposition 2, we derive the equilibrium decisions of the manufacturer. Next, by substituting those results into Proposition 1, we derive the equilibrium decisions of the TPR. All of the decisions are shown by the following proposition.

Proposition 4. *The equilibrium decisions of the manufacturer and the TPR are as follows, respectively:*

$$Q_{N-LR} = \begin{cases} \frac{1-c_N}{4}, & \text{if } 0 \le c_N < \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \\ \frac{\delta\beta-\beta(c_R-g)+\alpha}{2\delta\beta}, & \text{if} \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_N < c_N{}' \\ \frac{2(1+\delta\beta)(1-c_N)-\delta[\delta\beta-\beta(c_R-g)+\alpha]}{4(2+2\delta\beta-\delta^2\beta)}, & \text{if } c_N{}' \le c_N, \end{cases}$$

$$p_S = \begin{cases} \max\left\{\frac{\delta\beta(3+c_N)-4\beta(c_R-g)+4\alpha}{2\beta}, 0\right\}, & \text{if } 0 \le c_N < \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \\ \frac{\delta\beta-\beta(c_R-g)+\alpha}{2\beta}, & \text{if } \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_N < c_N{}' \\ \frac{\delta\beta-\beta(c_R-g)+\alpha}{2\beta}, & \text{if } c_N{}' \le c_N, \end{cases}$$

$$Q_R = \begin{cases} 0, & \text{if } 0 \le c_N < c_N{}' \\ \frac{(4+4\delta\beta-\delta^2\beta)[\delta\beta-\beta(c_R-g)+\alpha]-2\delta\beta(1+\delta\beta)(1-c_N)}{8(1+\delta\beta)(2+2\delta\beta-\delta^2\beta)} & \text{if } c_N{}' \le c_N. \end{cases}$$

The optimal quantities of the new products are shown in Figure 5. Moreover, from Propositions 3 and 4, we see that when the production cost is in the interval $\max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \leq c_N < c_N{}'$, both $\frac{\beta(c_R-g)-\alpha}{\delta\beta} < \frac{1-c_N}{2}$ and $\frac{\delta\beta-\beta(c_R-g)+\alpha}{2\delta\beta} > \frac{1-c_N}{4}$ hold. That is, the supplier strategically prevents the manufacturer from developing technology licensing remanufacturing by setting a wholesale price lower than that under a no-remanufacturing model.

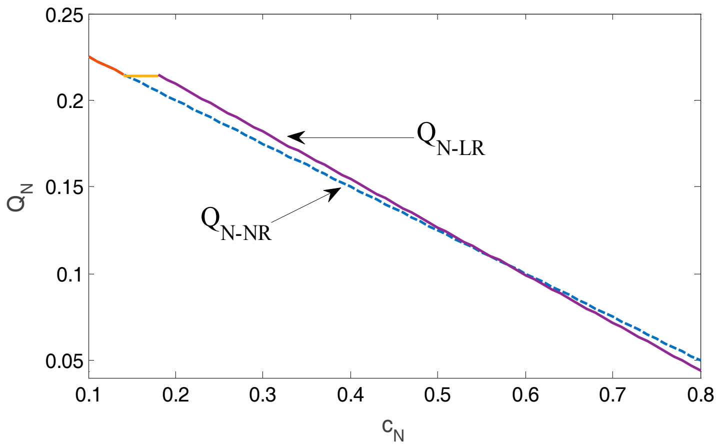

Figure 5. The optimal quantities of the new products ($c_R = 0.4$, $\alpha = 0$, $g = 0$, $\delta = 0.7$).

From Proposition 4, we have two other important findings, which are summarized in Corollaries 4 and 5.

Corollary 4. *Remanufactured products do not always cannibalize the market for new products.*

According to previous research (e.g., Atasu et al. [12] and Zou et al. [3]), a remanufactured product usually cannibalizes the market of a new product, no matter who carries out the remanufacturing. However, in our study, the supplier, as the upstream of the supply chain, may reduce the wholesale price so as to induce the manufacturer to abandon technology licensing remanufacturing operations or reduce the quantity of remanufactured products. In this case, a lower wholesale price induces the manufacturer to order more components for the new products, even though the manufacturer has developed technology licensing remanufacturing. Only when the production cost of the new product is high enough will the quantity of new products ordered by the manufacturer in model LR be lower than that in model NR.

Corollary 5. *License fees are independent of the production cost of the new product when the manufacturer develops licensing remanufacturing.*

This is a pretty counter-intuitive result. Intuitively, the production cost of new products will affect the decision of wholesale price by suppliers, which will in turn affect the quantity of orders the manufacturer makes for new products. Moreover, the order quantity of new products will affect the clearing price of new products and remanufactured products, which finally affects the marginal profits of the two products. It is common sense that the clearing price varying will force the manufacturer to adjust the license fee. Surprisingly, in model LR, we find the license fee is independent of the cost of the new product.

Recall the following manufacturer's decision problem after developing licensing remanufacturing (Equation (14)),

$$\max_{Q_N, p_S} \Pi_{M-LR} = (1 - Q_N - w)Q_N + \frac{(p_S - \delta Q_N)[\delta\beta(1 - Q_N) - \beta(c_R + p_S - g) + \alpha]}{2(1 + \delta\beta)},$$

which can be rewritten as

$$\max_{Q_{\mathrm{N}},p_{\mathrm{S}}} \Pi_{\mathrm{M-LR}} = \left(1 - Q_{\mathrm{N}} - w - \frac{\delta^2\beta(1-Q_{\mathrm{N}}) - \delta\beta(c_{\mathrm{R}}-g) + \delta\alpha}{2(1+\delta\beta)}\right)Q_{\mathrm{N}} + \frac{p_{\mathrm{S}}[\delta\beta - \beta(c_{\mathrm{R}}+p_{\mathrm{S}}-g)+\alpha]}{2(1+\delta\beta)}.$$

From this, we find that the first term is only related to Q_{N}, while the second term is related to p_{S}. That is to say, the manufacturer faces a problem where the decision variables are separated. How do Q_{N} and p_{S} interact with each other? In fact, Q_{N} affects p_{S} indirectly by means of affecting Q_{R}.

By substituting the derived results of Propositions 3 and 4 into the profit functions of supply chain members, we obtain the equilibrium profits, as shown in Proposition 5.

Proposition 5. *The equilibrium profits of the supplier, the manufacturer, and the TPR are as follows, respectively:*

$$\Pi_{\mathrm{S-LR}} = \begin{cases} \frac{(1-c_{\mathrm{N}})^2}{8}, & \text{if } 0 \le c_{\mathrm{N}} < \max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \\ \frac{[\beta(c_{\mathrm{R}}-g)-\alpha-\delta\beta c_{\mathrm{N}}][\delta\beta-\beta(c_{\mathrm{R}}-g)+\alpha]}{2\delta^2\beta^2}, & \text{if } \max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_{\mathrm{N}} < c_{\mathrm{N}}' \\ \frac{\{2(1+\delta\beta)(1-c_{\mathrm{N}})-\delta[\delta\beta-\beta(c_{\mathrm{R}}-g)+\alpha]\}^2}{16(1+\delta\beta)(2+2\delta\beta-\delta^2\beta)}, & \text{if } c_{\mathrm{N}}' \le c_{\mathrm{N}}, \end{cases}$$

$$\Pi_{\mathrm{M-LR}} = \begin{cases} \frac{(1-c_{\mathrm{N}})^2}{16}, & \text{if } 0 \le c_{\mathrm{N}} < \max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \\ \frac{[\delta\beta-\beta(c_{\mathrm{R}}-g)+\alpha]^2}{2\delta^2\beta^2}, & \text{if } \max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_{\mathrm{N}} < c_{\mathrm{N}}' \\ \frac{[\delta\beta-\beta(c_{\mathrm{R}}-g)+\alpha]^2}{8\beta(1+\delta\beta)} + \frac{\{2(1+\delta\beta)(1-c_{\mathrm{N}})-\delta[\delta\beta-\beta(c_{\mathrm{R}}-g)+\alpha]\}^2}{32(1+\delta\beta)(2+2\delta\beta-\delta^2\beta)}, & \text{if } c_{\mathrm{N}}' \le c_{\mathrm{N}} \end{cases}$$

$$\Pi_{\mathrm{TPR-LR}} = \begin{cases} 0, & \text{if } 0 \le c_{\mathrm{N}} < c_{\mathrm{N}}' \\ \frac{\left\{\left(4+4\delta\beta-\delta^2\beta\right)[\delta\beta+\alpha-\beta(c_{\mathrm{R}}-g)]-2\delta\beta(1+\delta\beta)(1-c_{\mathrm{N}})\right\}^2}{8\beta(1+\delta\beta)(2+2\delta\beta-\delta^2\beta)^2}, & \text{if } c_{\mathrm{N}}' \le c_{\mathrm{N}} \end{cases}$$

To illustrate the equilibrium profits of the supplier and the manufacturer for model NR and model LR, we plot them in Figures 6 and 7.

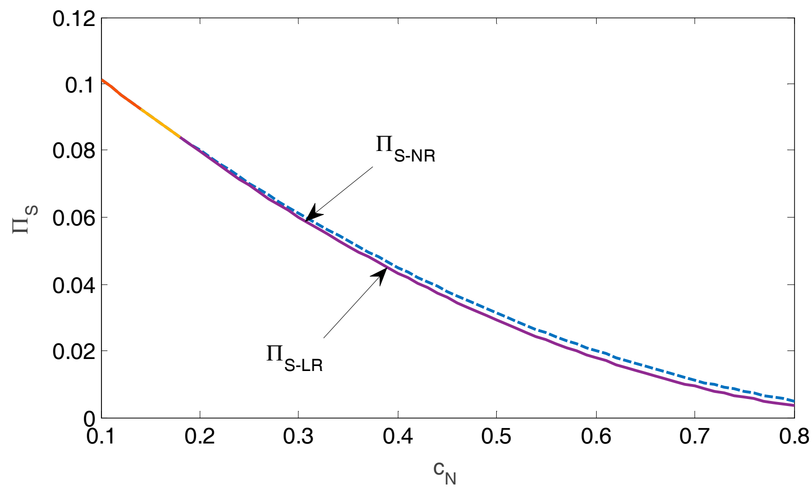

Figure 6. The profit of the supplier ($c_{\mathrm{R}} = 0.4$, $\alpha = 0$, $g = 0$, $\delta = 0.7$).

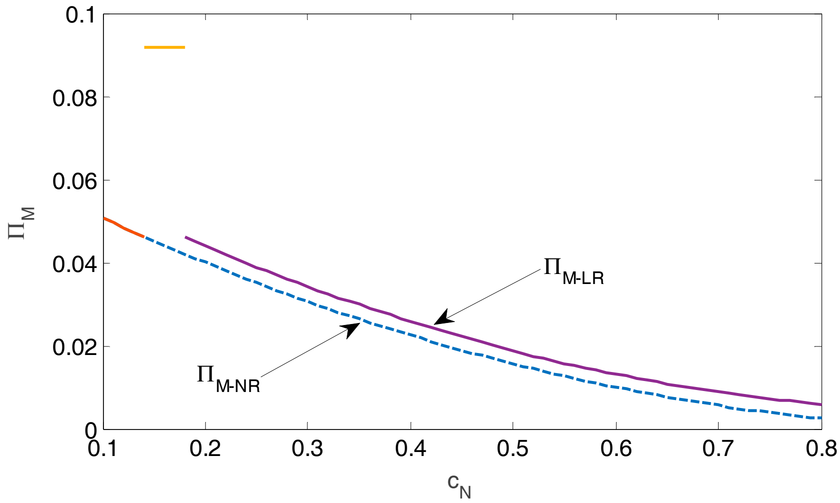

Figure 7. The profit of the manufacturer ($c_R = 0.4$, $\alpha = 0$, $g = 0$, $\delta = 0.7$).

Next, from the equilibrium results in Proposition 5, we can also derive the following results related to the double marginalization effect of this supply chain:

Corollary 6. *When the production cost of the new product satisfies* $\max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_N < c_N{}'$, *the double marginalization effect of the supply chain can be mitigated.*

Corollary 6 shows that the double marginalization effect of the supply chain has been mitigated, because when $\max\{(2\beta(c_R-g)-2\alpha-\delta\beta)/(\delta\beta), 0\} \le c_N < c_N{}'$, the supplier's wholesale price is $[\beta(c_R-g)-\alpha]/(\delta\beta) < (1+c_N)/2$, the sale price of the manufacturer is $[\delta\beta+\beta(c_R-g)-\alpha]/(2\delta\beta) < (3+c_N)/4$ and the total profit of the supply chain is greater than $3(1-c_N)^2/16$, i.e., the total profit of the supply chain in model NR.

Corollary 7. *The remanufactured product increases the manufacturer's profits, such that the manufacturer can even induce the supplier to compromise more profits by threatening to develop licensing remanufacturing.*

From the profit function of the manufacturer in Proposition 5, when $c_N{}' \le c_N$, the profit difference between model LR and model NR is

$$\begin{aligned}\Pi_{M-LR} - \Pi_{M-NR} &= \frac{[\delta\beta-\beta(c_R-g)+\alpha]^2}{8\beta(1+\delta\beta)} + \frac{\{2(1+\delta\beta)(1-c_N)-\delta[\delta\beta-\beta(c_R-g)+\alpha]\}^2}{32(1+\delta\beta)(2+2\delta\beta-\delta^2\beta)} - \frac{(1-c_N)^2}{16} \\ &= \frac{3[\delta\beta-\beta(c_R-g)+\alpha]^2}{32\beta(1+\delta\beta)} + \frac{\{\delta\beta(1-c_N)-[\delta\beta-\beta(c_R-g)+\alpha]\}^2}{16\beta(2+2\delta\beta-\delta^2\beta)} > 0,\end{aligned}$$

which implies that the existence of remanufactured product increases the manufacturer's profit.

Next, we deal with the proof of the rest of Corollary 7. When the production cost of the new product satisfies $\max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_N < c_N{}'$, the supplier provides compensation to the manufacturer at a lower wholesale price, and the manufacturer's profit satisfies the following relationship:

$$\Pi_{M-LR} - \Pi_{M-NR} \ge \frac{[\delta\beta-\beta(c_R-g)+\alpha]^2}{4\delta^2\beta^2} > 0,$$

Actually, we have $\Pi_{M-LR} \ge 2\Pi_{M-NR}$ holds. The result states that, to prevent remanufactured products from cannibalizing the market of the new product, the supplier provides the components to the manufacturer at a low wholesale price and gives more profits to subordinate the manufacturer. At this time, the manufacturer's profit increases significantly.

5. Environment-Related Analysis

In this section, we first analyze the effect of customer environmental awareness on remanufacturing decisions and the equilibrium results. Then we discuss how the licensing remanufacturing affects the environment.

5.1. Effect of Customer Environmental Awareness

Now we discuss the impact of customer environmental awareness on remanufacturing decisions.

From Figure 8, we find that as the customer environmental awareness grows, region VNR and FNR gradually decrease but region R gradually expands. That is to say, with the growing customer environmental awareness, the manufacturer has a stronger incentive to adopt licensing remanufacturing. Furthermore, as the customer environmental awareness grows, the size of the region FNR reduces, which implies that the supplier lowering the wholesale price to induce the manufacturer to abandon licensing remanufacturing becomes much more difficult.

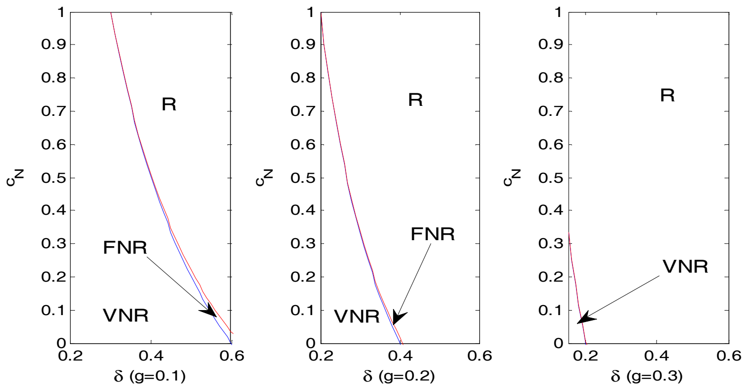

Figure 8. Effect of customer environmental awareness on equilibrium regions in model LR ($c_R = 0.4$, $\alpha = 0$).

Next, we conduct a sensitivity analysis of the decisions on customer awareness.

Proposition 6. *The sensitivity analysis of the decision variables with customer environmental awareness are as follows, respectively:*

$$\frac{\partial w_S}{\partial g} = \begin{cases} 0, & \text{if } 0 \le c_N < \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \\ -\frac{1}{\delta}, & \text{ifmax}\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_N < c_N{}' \\ -\frac{\delta\beta}{4(1+\delta\beta)}, & \text{if } c_N{}' \le c_N \end{cases}$$

$$\frac{\partial Q_{N-LR}}{\partial g} = \begin{cases} 0, & \text{if } 0 \le c_N < \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \\ \frac{1}{2\delta}, & \text{if } \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_N < c_N{}' \\ -\frac{\delta\beta}{4(2+2\delta\beta-\delta^2\beta)}, & \text{if } c_N{}' \le c_N \end{cases}$$

$$\frac{\partial p_S}{\partial g} = \begin{cases} 2/0, & \text{if } 0 \le c_N < \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \\ \frac{1}{2}, & \text{if } \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_N < c_N{}' \\ \frac{1}{2}, & \text{if } c_N{}' \le c_N \end{cases}$$

$$\frac{\partial Q_R}{\partial g} = \begin{cases} 0, & \text{if } 0 \le c_N < c_N{}' \\ \frac{\beta\left(4+4\delta\beta-\delta^2\beta\right)}{8(1+\delta\beta)(2+2\delta\beta-\delta^2\beta)}, & \text{if } c_N{}' \le c_N \end{cases}$$

Proposition 6 shows that with the growing customer environmental awareness, the supplier will lower the wholesale price when the manufacturer has an incentive to develop licensing remanufacturing operation. Due to $-1/\delta < -\delta\beta/4(1+\delta\beta)$, the supplier lowers the wholesale price more rapidly in region FNR than in region R. Therefore, as $\partial Q_{N-LR}/\partial g$ shows, the quantity of the new product increases in region FNR but decreases in region R. According to $\partial Q_R/\partial g$ and $\partial p_S/\partial g$, we find that, with the growing customer environmental awareness, TPR has a stronger incentive to remanufacture, and the manufacturer can share a higher payment.

5.2. *Effect of Technology Licensing Remanufacturing Operations*

In this subsection, we discuss how the licensing remanufacturing affects the environment. Following Raz et al. [34], Atasu and Souza [35] and Örsdemir et al. [36], we denote the environmental impacts of per-unit new product and per-unit remanufactured product as e_N and e_R, respectively. These two impacts mainly include those emissions during the manufacturing stage, use stage, and EOL stage. Empirical evidence (e.g., Hauser and Lund [5]) shows that as some components are reused, fewer raw materials and less energy need to be consumed to produce a remanufactured product than to produce a new product. Thus we assume $e_N > e_R$. According to these assumptions, the total environment impacts of the production in model NR and model LR are as follows, respectively:

$$E_{NR} = e_N Q_{N-NR} = \frac{(1-c_N)e_N}{4},$$

$$E_{LR} = e_N Q_{N-LR} + e_R Q_{R-LR}$$
$$= \begin{cases} \frac{(1-c_N)e_N}{4}, & \text{if } 0 \le c_N < \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \\ \frac{[\delta\beta-\beta(c_R-g)+\alpha]e_N}{2\delta\beta}, & \text{if } \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_N < c_N{}' \\ \frac{\{2(1+\delta\beta)(1-c_N)-\delta[\delta\beta-\beta(c_R-g)+\alpha]\}e_N}{4(2+2\delta\beta-\delta^2\beta)} + & \\ \frac{\{(4+4\delta\beta-\delta^2\beta)[\delta\beta-\beta(c_R-g)+\alpha]-2\delta\beta(1+\delta\beta)(1-c_N)\}e_R}{8(1+\delta\beta)(2+2\delta\beta-\delta^2\beta)}, & \text{if } c_N{}' \le c_N. \end{cases}$$

According to the definitions of E_{NR} and E_{LR}, we derive Proposition 7 as follows:

Proposition 7. *When* $0 \le c_N < \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\}$, *we have* $E_{NR} = E_{LR}$; *when* $\max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \le c_N < c_N{}'$, *we have* $E_{NR} < E_{LR}$; *when* $c_N{}' \le c_N$, *if* $\frac{e_R}{e_N} > \Delta$, *then we have* $E_{NR} < E_{LR}$, *otherwise, we have* $E_{NR} \ge E_{LR}$. *Here,* $\Delta = \frac{2\delta(1+\delta\beta)[\delta\beta c_N-\beta(c_R-g)+\alpha]}{(4+4\delta\beta-\delta^2\beta)[\delta\beta-\beta(c_R-g)+\alpha]-2\delta\beta(1+\delta\beta)(1-c_N)}$.

It is widely believed that remanufacturing reduces the environmental impacts (e.g., Atasu et al. [37], Souza [38]). However, according to Proposition 7, this is not true. The main reason is that a remanufactured product cannibalizes the market of the new product, which results in a decreased quantity of the new product produced by the manufacturer. Nevertheless, in order to induce the manufacturer to give up technology licensing remanufacturing or reduce the quantity of remanufactured products, the supplier dramatically reduces the wholesale price of the new product, which leads to more components for the new products being ordered by the manufacturer in most cases. Therefore, in most cases, the quality of the environment seldom improves. Only when the environmental impact of remanufactured products is remarkably lower than that of the new product, i.e., $e_R/e_N > \Delta$, and the production cost of the new product is high enough, i.e., $c_N{}' \le c_N$, can developing licensing remanufacturing be beneficial to the environment.

Next, we conduct a sensitivity analysis on customer awareness.

Corollary 8. *The sensitivity analysis of the total environmental impact with customer environmental awareness is*

$$\frac{\partial E_{\mathrm{LR}}}{\partial g}=\begin{cases}0, & \text{if } 0\le c_{\mathrm{N}}<\max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta},0\right\}\\ \frac{e_{\mathrm{N}}}{2\delta}, & \text{if } \max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta},0\right\}\le c_{\mathrm{N}}<c_{\mathrm{N}}{}'\\ \frac{\beta\left(4+4\delta\beta-\delta^2\beta\right)e_{\mathrm{R}}-2\delta\beta(1+\delta\beta)e_{\mathrm{N}}}{8(1+\delta\beta)(2+2\delta\beta-\delta^2\beta)}, & \text{if } c_{\mathrm{N}}{}'\le c_{\mathrm{N}}\end{cases}$$

From Corollary 8, we find that when $\max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta},0\right\}\le c_{\mathrm{N}}<c_{\mathrm{N}}{}'$, customer environmental awareness does not improve the environment but in fact harms it. When $c_{\mathrm{N}}{}'\le c_{\mathrm{N}}$, only if $\frac{e_{\mathrm{R}}}{e_{\mathrm{N}}}<\frac{2\delta(1+\delta\beta)}{4+4\delta\beta-\delta^2\beta}$, customer environmental awareness can improve the environment.

6. Conclusions and Future Research

In this paper, we propose an analytical model to study a closed-loop supply chain consisting of one supplier, one manufacturer, and one TPR, where the manufacturer adopts technology licensing remanufacturing via the TPR and customer environmental awareness is taken into account. To discuss the impact of the licensing remanufacturing, we consider a model with remanufacturing and one with no remanufacturing. The optimal operational decisions are derived and compared. Our main findings include the following two perspectives:

- From the supply chain perspective, we find that when remanufacturing is a potential threat to the supplier, the performance of the supply chain is improved and the double marginalization effect is effectively eliminated. Moreover, we find that remanufacturing by technology licensing only improves the profit of the manufacturer, but harms the profit of the supplier. Therefore, in order to induce the manufacturer to abandon licensing remanufacturing or decrease the quantity of remanufactured products, the supplier may lower the wholesale price of the components. Interestingly, contrary to traditional wisdom, the existence of remanufactured products does not reduce the quantity of new products. This result is different from the existing literature (such as Zou et al. [3] and Atasu et al. [12]), in which remanufactured products usually cannibalize the market of new products, no matter who carries out the remanufacturing.
- From an environmental perspective, we see from Section 5.1 that, as customer environmental awareness grows, the manufacturer has a stronger incentive to adopt licensing remanufacturing, but the supplier may lower the wholesale price to induce the manufacturer to abandon this strategy. However, only under certain conditions will the manufacturer abandon licensing remanufacturing when the supplier lowers its wholesale price. Moreover, we find from the analysis in Section 5.2 that remanufacturing by technology licensing may not always make the environment better, although the customers in the market have environmental awareness that facilitates remanufacturing. This result is also different from Atasu et al. [37] and Souza [38], where remanufacturing reduces the environmental impacts.

It is worth noting that the above main findings not only answer the research questions raised before, but also provide important insights for manufacturers who want to adopt licensing remanufacturing, and for suppliers who provide components for the above manufacturer during their operations. For example, the findings of the paper illustrate that the manufacturer can improve bargaining power with the supplier via developing technology licensing remanufacturing operations. However, this strategy may lead to an excessive supply of products which, in turn, increases the environmental burden on the whole of society. Therefore, the government should pay careful attention to cases in which a manufacturer develops remanufacturing operations to improve its bargaining power with a supplier. In this case, the government can induce the supplier to provide much “greener” products or components through a subsidy policy or tax reduction policy, rather than encouraging the manufacturer to develop remanufacturing operations. Furthermore, our findings provide a guide for suppliers to make decisions when facing such manufacturers. For example, if a supplier finds that his customers or manufacturers adopt remanufacturing operations, they may try to ask for more subsidies or a greater tax reduction from the government so as to protect the environment.

This paper is an attempt to consider the effect of technology licensing in a closed-loop supply chain with the consideration of customers' environmental awareness. There are several limitations of our model setting, which also point towards possible future research directions. Firstly, our model does not consider the uncertainty of demand and remanufacturing costs, which always exist in real practice. Therefore, one possible future direction is to study the models with uncertainty demand or remanufacturing costs, where the risk behaviors or the information sharing of the supply chain members can also be considered (Lai et al. [39], Shen et al. [40], Shen and Chan [41]). Secondly, we assume that the TRP paid the licensing fee to the manufacturer based on per unit product. In practice, licensing fees can take other forms, such as a fixed licensing fee, a royalty licensing fee, or revenue sharing (Hong et al. [7], Oraiopoulos et al. [14]). Comparing the effects of these licensing fee forms could be another interesting future direction. Finally, our model includes only one manufacturer (one supplier) and does not consider the competition between manufacturers (suppliers), which is not the case in the real world. It would be of interest for us to consider settings with multiple players, such as multiple suppliers or multiple manufacturers, in the future.

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Appendix A All proofs

Proof of Proposition 1. We define the Lagrangian function

$$L(Q_{R-LR}) = \left(\delta(1 - Q_{N-LR} - Q_{R-LR}) + g - c_R - p_S - \frac{Q_{R-LR} - \alpha}{\beta}\right) Q_{R-LR} + \lambda Q_{R-LR},$$

where the KT conditions are:

$$\begin{cases} \delta(1 - Q_N - 2Q_R) + g - c_R - p_S - \frac{2Q_R - \alpha}{\beta} + \lambda = 0 \\ \lambda Q_R = 0 \end{cases}.$$

Based on the value of λ, we have:

(a) When $\lambda = 0$, that is, $\frac{\delta\beta(1-Q_N)+\beta g-\beta c_R+\alpha}{\beta} \geq p_S$,

$$Q_R = \frac{\delta\beta(1 - Q_N) - \beta(c_R + p_S - g) + \alpha}{2(1 + \delta\beta)}.$$

(b) When $\lambda > 0$, that is $p_S > \frac{\delta\beta(1-Q_N)+\beta g-\beta c_R+\alpha}{\beta}$,

$$Q_R = 0.$$

The above results lead to the remanufacturer's production decision:

- When $\frac{\delta\beta(1-Q_N)+\beta g-\beta c_R+\alpha}{\beta} \geq p_S \geq 0$, the remanufacturer conducts remanufacturing,
- and when $p_S > \frac{\delta\beta(1-Q_N)+\beta g-\beta c_R+\alpha}{\beta}$, the remanufacturer does not remanufacture.

□

Proof of Proposition 2. When $\delta\beta(1-Q_N)+\beta g-\beta c_R+\alpha \geq \beta p_S$, the remanufacturer conducts partial remanufacturing. Manufacturer's problem is reduced as follows:

$$\max_{Q_N,p_S} \Pi_{M-LR} = (1-Q_N-w)Q_N + \frac{(p_S-\delta Q_N)[\delta\beta(1-Q_N)-\beta(c_R+p_S-g)+\alpha]}{2(1+\delta\beta)}$$
$$\text{s.t. } \delta\beta(1-Q_N)+\beta g-\beta c_R+\alpha \geq \beta p_S$$

First we define the Lagrangian function:

$$L = \Pi_{M-LR} + \lambda_2(\delta\beta(1-Q_N)+\beta g-\beta c_R+\alpha-\beta p_S),$$

wherein the KT conditions are

$$\begin{cases} \frac{2(1+\delta\beta)(1-2Q_N-w)-\left(\delta^2\beta+\delta\beta g-\delta\beta c_R+\delta\alpha-2\delta^2\beta Q_N\right)}{2(1+\delta\beta)} - \lambda_2\delta\beta = 0 \\ \frac{\delta\beta+\beta g-\beta c_R+\alpha-2\beta p_S}{2(1+\delta\beta)} - \lambda_2\beta = 0 \\ \lambda_2[\delta\beta(1-Q_N)+\beta g-\beta c_R+\alpha-\beta p_S] = 0 \end{cases},$$

with $\lambda_2 \geq 0$. Based on the value of λ, we have:

(a) When $\lambda_2 = 0$, i.e., $\frac{\beta c_R-\beta g-\alpha}{\delta\beta} \leq w$, the remanufacturer conducts partial remanufacturing. The manufacturer's optimal decision combination is

$$\begin{cases} Q_N = \frac{2(1+\delta\beta)(1-w)-\delta(\delta\beta-\beta c_R+\beta g+\alpha)}{2(2+2\delta\beta-\delta^2\beta)} \\ p_S = \frac{\delta\beta+\beta g-\beta c_R+\alpha}{2\beta}. \end{cases}$$

At this time, the manufacturer's profit is

$$\Pi_{M-LR} = \frac{2\beta(1+\delta\beta)(1-w)^2+(\delta\beta+\beta g-\beta c_r+\alpha)^2-2\delta\beta(\delta\beta+\beta g-\beta c_r+\alpha)(1-w)}{4\beta(2+2\delta\beta-\delta^2\beta)}.$$

(b) When $\lambda_2 > 0$, that is $w < \frac{\beta c_R-\beta g-\alpha}{\delta\beta}$, the TPR does not remanufacture, and the manufacturer's optimal decision combination is

$$\begin{cases} Q_N = \frac{1-w}{2} \\ p_S = \frac{\delta\beta(1+w)-2\beta(c_R-g)+2\alpha}{2\beta}. \end{cases}$$

At this time, the profit of the manufacturer is

$$\Pi_{M-LR} = \frac{(1-w)^2}{4}.$$

For the second case, when $\delta\beta(1-Q_n)-\beta(c_r-g)+\alpha < \beta p_s$, the remanufacturer does not remanufacture, and the decision problem of the manufacturer can be reduced to

$$\max_{Q_N,p_S} \Pi_{M-LR} = (1-Q_N-w)Q_N$$
$$\text{s.t. } \delta\beta(1-Q_N)-\beta(c_R-g)+\alpha < \beta p_S.$$

The first-order condition leads to the optimal quantity of the manufacturer $Q_N = \frac{1-w}{2}$. Moreover, to prevent the participation of the remanufacturer, the license fee should satisfy $\frac{\delta\beta(1+w)-2\beta(c_R-g)+2\alpha}{2\beta} < p_S$. Therefore, the manufacturer's optimal decision combination is,

$$\begin{cases} Q_N = \frac{1-w}{2} \\ p_S = \frac{\delta\beta(1+w)-2\beta(c_R-g)+2\alpha}{2\beta}. \end{cases}$$

Then the profit of the manufacturer is

$$\Pi_{M-LR} = \frac{(1-w)^2}{4}.$$

Given the wholesale price w, the above results lead to the following optimal decisions of the manufacturer:

$$(Q_N, p_S) = \begin{cases} \left(\frac{1-w}{2}, \max\left\{\frac{\delta\beta(1+w)-2\beta(c_R-g)+2\alpha}{2\beta}, 0\right\}\right), & w \le \frac{\beta(c_R-g)-\alpha}{\delta\beta} \\ \left(\frac{2(1+\delta\beta)(1-w)-\delta[\delta\beta-\beta(c_R-g)+\alpha]}{2(2+2\delta\beta-\delta^2\beta)}, \frac{\delta\beta-\beta(c_R-g)+\alpha}{2\beta}\right), & \frac{\beta(c_R-g)-\alpha}{\delta\beta} < w. \end{cases}$$

□

Proof of Proposition 3. In the first case, the TPR does not recycle the EOL products, and the decision problem of the supplier is as follows:

$$\max_w \Pi_{S-LR} = \frac{(w-c_N)(1-w)}{2}$$
$$\text{s.t. } w \le \frac{\beta(c_R-g)-\alpha}{\delta\beta}.$$

Define the Lagrangian function $L = \frac{(w-c_N)(1-w)}{2} + \lambda\left(\frac{\beta(c_R-g)-\alpha}{\delta\beta} - w\right)$, wherein the KT conditions are:

$$\begin{cases} \frac{1-2w+c_N}{2} - \lambda = 0 \\ \lambda\left(\frac{\beta(c_R-g)-\alpha}{\delta\beta} - w\right) = 0 \end{cases}$$

Based on the value of λ, we have:

(a) When $\lambda = 0$, that is $c_N \le \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\}$, the wholesale price of the supplier is

$$w = \frac{1+c_N}{2}$$

The profit of the supplier is

$$\Pi_{S-LR} = \frac{(1-c_N)^2}{8}.$$

(b) When $\lambda > 0$, that is $c_N > \max\left\{\frac{2\beta(c_R-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\}$, the wholesale price of the supplier is

$$w = \frac{\beta(c_R-g)-\alpha}{\delta\beta}.$$

The profit of the supplier is

$$\Pi_{S-LR} = \frac{[\beta(c_R-g)-\alpha-\delta\beta c_N][\delta\beta+\alpha-\beta(c_R-g)]}{2\delta^2\beta^2}.$$

In the second case, the TPR recycles the EOL products, and the decision problem for the supplier is as follows:

$$\max_{w} \Pi_{\mathrm{S-LR}} = \frac{(w-c_{\mathrm{N}})\{2(1+\delta\beta)(1-w)-\delta[\delta\beta-\beta(c_{\mathrm{R}}-g)+\alpha]\}}{2(2+2\delta\beta-\delta^{2}\beta)}$$
$$\text{s.t. } \frac{\beta(c_{\mathrm{R}}-g)-\alpha}{\delta\beta} < w$$

Define the Lagrangian function as follows:

$$L = \Pi_{\mathrm{S-LR}} + \lambda_1\left(w - \frac{\beta(c_{\mathrm{R}}-g)-\alpha}{\delta\beta}\right),$$

wherein the KT conditions are

$$\begin{cases} \frac{2(1+\delta\beta)(1-w)-\left[\delta^{2}\beta-\delta\beta(c_{\mathrm{R}}-g)+\delta\alpha\right]-2(1+\delta\beta)(w-c_{\mathrm{N}})}{2(2+2\delta\beta-\delta^{2}\beta)} + \lambda_1 = 0 \\ \lambda_1\left(w - \frac{\beta(c_{\mathrm{R}}-g)-\alpha}{\delta\beta}\right) = 0 \end{cases}.$$

Based on the value of λ, we have:

(a) When $\lambda_1 > 0$, that is $c_{\mathrm{N}} < \frac{\left(4+4\delta\beta-\delta^{2}\beta\right)[\beta(c_{\mathrm{R}}-g)-\alpha]-\delta\beta\left(2+2\delta\beta-\delta^{2}\beta\right)}{2\delta\beta(1+\delta\beta)}$, the optimal wholesale price of the supplier is:

$$w = \frac{\beta(c_{\mathrm{R}}-g)-\alpha}{\delta\beta}.$$

The profit of the supplier is,

$$\Pi_{\mathrm{S-LR}} = \frac{[\beta(c_{\mathrm{R}}-g)-\alpha-\delta\beta c_{\mathrm{N}}][\delta\beta+\alpha-\beta(c_{\mathrm{R}}-g)]}{2\delta^{2}\beta^{2}}.$$

(b) When $\lambda_1 = 0$, that is $c_{\mathrm{N}} \geq \frac{\left(4+4\delta\beta-\delta^{2}\beta\right)[\beta(c_{\mathrm{R}}-g)-\alpha]-\delta\beta\left(2+2\delta\beta-\delta^{2}\beta\right)}{2\delta\beta(1+\delta\beta)}$, the optimal wholesale price of the supplier is

$$w = \frac{1+c_{\mathrm{N}}}{2} - \frac{\delta^{2}\beta-\delta\beta(c_{\mathrm{R}}-g)+\delta\alpha}{4(1+\delta\beta)}.$$

The profit of the supplier is

$$\Pi_{\mathrm{S-LR}} = \frac{[\delta\beta+\alpha-\beta(c_{\mathrm{R}}-g)]\{(2+3\delta\beta)(1-c_{\mathrm{N}})-(1+\delta)[\delta\beta+\alpha-\beta(c_{\mathrm{R}}-g)]\}}{2(2+3\delta\beta)^{2}}$$

Therefore, the above results yield the following wholesale decisions for the supplier:

$$w_{\mathrm{LR}} = \begin{cases} \frac{1+c_{\mathrm{N}}}{2}, & \text{if } 0 \leq c_{\mathrm{N}} < \max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \\ \frac{\beta(c_r-g)-\alpha}{\delta\beta}, & \text{if} \max\left\{\frac{2\beta(c_{\mathrm{R}}-g)-2\alpha-\delta\beta}{\delta\beta}, 0\right\} \leq c_{\mathrm{N}} < \frac{\left(4+4\delta\beta-\delta^{2}\beta\right)[\beta(c_{\mathrm{R}}-g)-\alpha]-\delta\beta\left(2+2\delta\beta-\delta^{2}\beta\right)}{2\delta\beta(1+\delta\beta)} \\ \frac{1+c_{\mathrm{N}}}{2} - \frac{\delta[\delta\beta-\beta(c_{\mathrm{R}}-g)+\alpha]}{4(1+\delta\beta)}, & \text{if } \frac{\left(4+4\delta\beta-\delta^{2}\beta\right)[\beta(c_{\mathrm{R}}-g)-\alpha]-\delta\beta\left(2+2\delta\beta-\delta^{2}\beta\right)}{2\delta\beta(1+\delta\beta)} \leq c_{\mathrm{N}}. \end{cases}$$

□

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