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Only the Friendly Face? The Consequences of Consumer Education for Green Consumerism in Remanufacturing

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Abstract: Empirical studies suggest that investing in consumer education on green consumption not only naturally induces environmental sustainability but also yields various economic benefits for the original equipment manufacturers (OEMs). However, as far as we know, these studies overlook the potential cannibalization of new product sales. By developing a theoretical model that involves consumer education on green consumption when choosing between in-house or outsourcing remanufacturing, we find that if allowing the flexibility of remanufacturing outsourcing, consumer education on green consumption introduces opportunities for opportunistic behaviors that can compromise both profitability and environmental objectives. Specifically, when OEMs engage in remanufacturing, either in-house or through outsourcing, we observe that the incentive to invest in consumer education on green consumption is greater for in-house remanufacturing compared to outsourcing. This heightened incentive for consumer education enables OEMs to maintain higher profits under remanufacturing in-house, which results in a threat to environmental sustainability.

Keywords: green/sustainable supply chains; consumer education; sustainability investment; game theory

Citation: Sun, L.; Yuan, Q. Only the Friendly Face? The Consequences of Consumer Education for Green Consumerism in Remanufacturing. *Sustainability* **2024**, *16*, 7411. https://doi.org/10.3390/su16177411

Academic Editors: Alberto Ferriz-Valero and Salvador Baena-Morales

Received: 16 July 2024
Revised: 21 August 2024
Accepted: 22 August 2024
Published: 28 August 2024

1. Introduction

Remanufacturing involves recycling of used products, refurbishing and selling them again [1,2]. As such, remanufacturing is an effective strategy that diverts materials from landfills, yielding sustainable benefits. Despite efforts by both governmental agencies and industries to encourage remanufacturing, only a few consumers are willing to purchase remanufactured products [3]. Factors, such as attitudes, consumer perceptions, and subjective norms, serve as significant barriers to purchasing remanufactured products [4,5].

In response to these barriers, successful consumer education on green consumption is recognized as an effective method that can help consumers to make informed choices [4,6]. In practice, to divert materials from landfills, there are increasing government efforts to increase consumer education on green consumption. For instance, concerning WEEE, a visible fee should be levied to assist in educating consumers [7]. Similarly, the central government of China issued Opinions on Promoting the Development of the Remanufacturing Sector to support consumer education concerning remanufacturing [8].

The empirical literature suggests that investing in consumer education on green consumption not only naturally induces environmental sustainability but also yields various economic benefits for the OEM. For example, in the remanufacturing industry, successful consumer education on green consumption can increase the willingness to pay for the remanufactured products by as much as 16.8% [4,9]. As such, to obtain economic benefits, many pioneers, such as Apple, Boeing and Xerox have invested in consumer education on sustainability in relation to remanufacturing activities [6,10]. These brands believe the consumer education can meet corporate sustainability goals that "...can put our impact and our customers' impact on the environment and help society", as articulated by John Visentin, Vice Chairman and CEO of Xerox [11].

However, although recent empirical evidence and experimental results (e.g., Khor and Hazen [4], Tully and Winer [9], and Wang [12]) have recognized various economic and sustainable benefits for the OEM, they overlook the potential cannibalization of new product sales. On the other hand, Zhou, Xiong [6] identified a consumer education paradox, indicating that as consumers become more willing to pay for remanufactured products, the OEM is more likely to shift from remanufacturing to no remanufacturing. This paradoxical result is attributed to the OEM's reluctance to lose control over cannibalization effects from remanufactured products and their desire to not harm new products sales.

However, as far as we know, no formal theory highlights how differentiated organizational modes, namely, in-house or outsourcing, affect remanufacturing decisions under consumer education on green consumption. In practice, both modes are commonly observed in the remanufacturing industry: Many brand name firms like Xerox, IBM and Cannon engage in in-house remanufacturing, while third-party remanufacturers handle operations in the US, Europe, and Japan markets [13,14]. In the U.S.A remanufacturing industry, more than 96% of remanufacturing business is undertaken by the third-party remanufacturers [15,16].

Inspired by the prior research of Zhou, Xiong [6], this paper aims to highlight how the remanufacturing decisions under consumer education on green consumption are impacted by different organizational modes. Specifically, this paper develops a theoretical model that highlights the manufacturer's incentives to invest in consumer education on green consumption when choosing between in-house or outsourcing remanufacturing. The following research questions are addressed:

How does the organizational mode of remanufacturing, i.e., in-house or outsourcing, affect the manufacturer's incentives in consumer education on green consumption?

What effects does an increase in consumer education on green consumption have on decisions, profits, and environmental performance?

Our findings confirm some intuitive expectations that consumer education on green consumption can increase the willingness to pay for the remanufactured products. However, in contrast to conventional wisdom that environmental concerns are presumably part of promoting consumer education, we demonstrate that, if allowing the flexibility of remanufacturing outsourcing, consumer education on green consumption creates opportunities for opportunistic behaviors in profitability and environmental goals. Specifically, we observe that the incentive to invest in consumer education on green consumption is greater for in-house remanufacturing compared to outsourcing. This higher incentive for consumer education allows the OEM to maintain higher profit margins from remanufactured units. However, such a higher incentive may damage environmental sustainability due to an increase in the production of new products.

The remainder of the paper is organized as follows. Section 2 presents the literature review. In Section 3, we lay out the assumptions and introduce the notation used. Section 4 develops two models and derives equilibrium solutions. Section 5 analyzes our results and reports our main findings. Section 6 provides a discussion and outlines future research directions.

2. Literature Review

This section outlines three related studies in remanufacturing that involved issues of consumer education, organizational modes and environmental sustainability. Table 1 provides a comparison of this study with the related research.

Table 1. Contributions of this paper.

Author(s)	Consumer Education	Organizational Modes	Environmental Sustainability
Zhou, Xiong [6], Wang, Yang [17], Yang, Chen [18], Mathew, Teoh [19], Sun and Liu [2]	√	✗	√
Zou, Wang [14], Zhang, Chen [20], Zhang, Chen [21], Yang, Hao [22], Lv, Guo [23]	✗	√	√
Wang, Cai [24], Agrawal, Ferguson [25], White, Stoughton [26], Yan, Xiong [27]	✗	✗	√
This paper	√	√	√

Several research streams have explored the role of consumer education within supply chains. Early studies primarily focused on understanding how consumer behavior is influenced by learning from others, e.g., Hitchcock [28], Liu, Hotta [29], Perry [30], and Shen, Zhu [31]. Given that consumer acceptance is a crucial barrier to purchasing remanufactured products [4,5], recent research has honed in on consumer education concerning green consumption in the context of remanufacturing scenarios. For example, Wang, Yang [17] investigated the impact of used products collection and remanufacturing capabilities on reverse channel designs, considering consumer education. Yang, Chen [18] employed simulation experiments to evaluate the effects of publicity, education, and social discussion on green consumption behavior. More recently, Mathew, Teoh [19] surveyed public actions and willingness towards the disposal, collection, and recycling of lithium-ion batteries in Malaysia. In the realm of game theory, Sun and Liu [2] developed a model to discuss optimal production decisions based on the level of consumer education. Notably, Zhou, Xiong [6] delved into a game theory model, identifying a consumer education paradox in a closed-loop supply chain where increasing consumer willingness to pay for remanufactured products leads OEMs to shift away from remanufacturing. As highlighted earlier, there is a gap in formal theory regarding how the organizational mode of remanufacturing, whether in-house or outsourcing, affects consumer education on green consumption. In practice, both modes are prevalent in the remanufacturing industry, prompting us to complement existing studies by emphasizing OEMs' incentives in consumer education under the choice between in-house or outsourcing remanufacturing.

Another pertinent research stream examines how different organizational modes impact remanufacturing decisions. Zou, Wang [14] developed models involving OEMs allowing third-party remanufacturers to perform operations through outsourcing or authorization. Zhang, Chen [20] focused on a competitive closed-loop supply chains under outsourcing and authorization modes. Additionally, Zhang, Chen [21] explored how OEM's capital constraints and financing behaviors influence their selection preferences regarding third-party remanufacturing. Yang, Hao [22] considered different collecting modes under cap-and-trade regulation, and Lv, Guo [23] developed simultaneous game models for unauthorized remanufacturing, authorized remanufacturing with unit authorization fees, and authorized remanufacturing with fixed authorization fees. While these studies do not specifically address the influence of differentiated remanufacturing modes and consumer education on green consumption, they serve as inspiration for our exploration into how in-house or outsourcing organizational modes affect remanufacturing decisions in the presence of consumer education about green consumption.

The final stream of the literature examines the environmental sustainability of remanufacturing. White, Stoughton [26] explored how the environmental impact depends on the volume of products in each phase. Similarly, Agrawal, Ferguson [25] assessed environmental performance by multiplying the volume with the per-unit impact. In contrast, Yan, Xiong [27] calculated environmental impacts by combining the total disposal impact of new products with the impacts of remanufacturing. Wang, Cai [24], rather than focusing on end customer usage, highlighted the environmental impact depending on the level of remanufacturing activity. Notably, previous studies on the environmental sustainability of remanufacturing have not thoroughly examined the consequences of consumer education on green consumption. In this regard, we present an alternative approach to underscore the impacts of consumer education about green consumption on both economic performance and environmental sustainability objectives.

3. Modeling Framework

This paper aims to investigate whether and how the organizational modes of remanufacturing affect OEM's decisions on green education and the subsequent impacts on economic performance and environmental sustainability. To achieve this, as the research plan in Figure 1 shows, two models are developed: In Model O, the OEM engages in remanufacturing in-house and undertakes public education on green consumption behavior, while in Model T, the OEM outsources the remanufacturing business to an independent third-party remanufacturer but still undertakes public education on green consumption behavior.

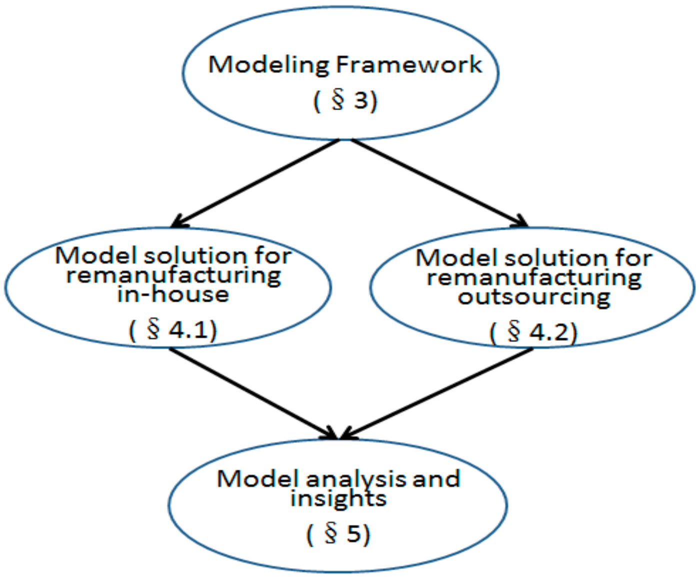


Figure 1. Research plan of this paper.

The timeline of decisions unfolds as follows: In the first stage, the OEM decides whether to provide public education on green consumption. In the second stage, the manufacturer sets the remanufacturing authorization fee f given to the third-party remanufacturer. Then, they simultaneously determine the optimal prices for the new product p_n and remanufactured product p_r.

For simplification, we normalize the consumer population of the market to 1. If the OEM chooses to invest in public education on green consumption behavior, the proportion β of the consumer population with green purchase behavior increases. It is important to note that, unlike strategic consumers who are only concerned for the function of the product, green consumers are environmentally conscious, and their level of concern for the environment may even surpass their concern for the product's function [17,32].

Following assumptions similar to those in Ho, Huang [33], and in Zhou, Xiong [6], ordinary consumers have a willingness to pay for the new product, denoted as v, and a willingness to pay for the remanufactured product, denoted as δv, where δ is the value discount for the remanufactured product and satisfies $\delta < 1$. Based on these assumptions, the net utility that ordinary consumers derive from the new product is denoted as $U_n^s = v - p_n$ (superscript s indicates strategic consumers), and the net utility they derive from the remanufactured product is denoted as $U_r^s = \delta v - p_r$. Therefore, when $U_n^s > U_r^s$, the ordinary consumers prefer the new product to the remanufactured one. However, for $U_n^s < U_r^s$, they choose the remanufactured one. Since the proportion of the consumer population with green purchasing behavior is β, then the demand functions for new products and remanufactured products for the strategic consumers are given by

$$\begin{array}{l} q_n^s = (1-\beta)(1-\frac{p_n-p_r}{1-\delta}) \\ q_r^s = (1-\beta)(\frac{\delta p_n-p_r}{(1-\delta)\delta}) \end{array} \quad (1)$$

To differentiate green consumers from ordinary consumers, we assume that green consumers perceive the remanufactured product as more environmentally friendly, so they only purchase the remanufactured product [6], with a willingness to pay denoted as v. Then, the net utility that green consumers derive from the remanufactured product is denoted as $U_r^g = v - p_r$ (superscript g indicates green consumers). Since green consumers' environmental concerns may surpass their concern for the product's function, for $U_r^g > 0$, green consumers will only purchase the remanufactured one. Then, their demand function is given by $q_r^s = \beta(1 - p_r)$.

Therefore, the total demand functions for new and remanufactured products are given by

$$\begin{array}{l} q_n = q_n^s = (1-\beta)(1-\frac{p_n-p_r}{1-\delta}) \\ q_r = q_r^s + q_r^g = (1-\beta)(\frac{\delta p_n-p_r}{(1-\delta)\delta}) + \beta(1-p_r) \end{array} \quad (2)$$

Additionally, it is assumed that the production costs for the new and remanufactured product are c_n and c_r, respectively. To highlight the cost differences between manufacturing and remanufacturing, it is further assumed that the unit cost of remanufactured product is lower than the production cost of the new product, and for simplicity, we normalize the unit cost of remanufacturing to zero, i.e., $c_n = c > c_r = 0$ [20,27]. Table 2 lists the related parameters in this paper.

Table 2. Definitions of the related variables.

Type	Variable	Definition
Parameters	v	Consumer willingness-to-pay for new products
	δ	The value discount for the remanufactured product
	n	New products
	r	Remanufactured products
	g	Green consumers
	c	The unit cost of production
	β	The consumer population employing green purchasing
	k	The incentive to invest in consumer education
	e	The total environmental impacts
	π	The OEM's profits
Decisions		
	f	The fees for remanufacturing outsourcing
	p	Price of new/remanufactured products

4. Equilibrium Outcomes

4.1. In-House Remanufacturing (Model O)

In Model O, both new products and remanufactured products are provided by the OEM. The sequence of events is as follows: In the first stage, the OEM decides whether to invest in public education on green consumption behavior; in the second stage, the OEM determines the optimal prices for the new product p_n and remanufactured product p_r. That is, the problem of the OEM can be expressed as follows:

$$\pi^O = (p_n - c_n)q_n + (p_r - c_r)q_r - \frac{K}{2}\beta^2 \quad (3)$$

where π^O is the profit and the first two terms represent the profits obtained by the OEM from selling new products and remanufactured products, respectively, while the last term represents the potential cost of investing in public education on green consumption behavior. By substituting the above inverse demand functions of (1) into Equation (3), we use backward induction to derive the optimal prices for the OEM in Table 3 (detailed proof can be found in Appendix A).

Table 3. Equilibrium decisions and profits.

In-House Remanufacturing (Model O)
$p_n^O = \frac{2\beta\delta+1-\beta-\beta\delta^2+\beta\delta c+c-c\beta}{2(\beta\delta+1-\beta)}$ $p_r^O = \frac{\delta}{2(\beta\delta+1-\beta)}$ $K^O = \frac{\left[\begin{array}{l} 1-3\delta-2c+2\delta c+c^2+2c\beta-\beta+3\beta\delta-4\beta\delta c \\ -3\beta\delta^2-c^2\beta+2\beta\delta^2 c+\beta c^2\delta+\beta\delta^3+3\delta^2-\delta^3 \end{array}\right]}{2\beta(\beta\delta+1-\beta)(\delta-1)}$ $\pi^O = \frac{\left[\begin{array}{l} \beta^2\delta^3-\beta\delta^3-3\beta^2\delta^2+2\beta^2\delta^2 c-2\beta\delta^2 c+4\beta\delta^2+3\beta^2\delta-4\beta^2\delta c+\beta^2\delta c^2+2c \\ -5\beta\delta+6\beta\delta c-\beta\delta c^2-2c\delta+\delta-\beta^2-c^2\beta^2+2c\beta^2+2c^2\beta-4c\beta+2\beta-1-c^2 \end{array}\right]}{4(\beta\delta+1-\beta)(\delta-1)}-\frac{K}{2}\beta^2$
Outsourced Remanufacturing (Model T)
$p_n^T = \frac{\left[\begin{array}{l} 2\beta\delta^2 c-2+3f\beta\delta^2-3f\beta\delta+2c\beta-2c-5\beta\delta \\ +3f\beta-2\beta\delta^3+2\delta-3f-2\beta\delta c+2\beta+5\beta\delta^2 \end{array}\right]}{4\beta+4\beta\delta^2-4+\delta-5\beta\delta}$ $p_r^T = \frac{2f\beta\delta^2-f\beta\delta-f\delta+2f\beta-\delta-2f+\beta\delta c+\beta\delta^2-\delta c+\delta^2-\beta\delta}{4\beta+4\beta\delta^2-4+\delta-5\beta\delta}$ $f = \frac{\delta\left[\begin{array}{l} \beta^3\delta c-\beta^3\delta^2 c-14\beta^2\delta^3-13\beta^2\delta+20\beta^2\delta^2-\beta\delta^2 c+2\beta^3\delta^2+8+3\beta\delta c-\beta^3\delta^3 \\ -\beta^3\delta-\beta\delta^3+2\beta^2\delta^2 c+13\beta\delta-3\beta^2\delta c+8\beta^2+8\beta^2\delta^4-\delta c-14\beta\delta^2+\delta-16\beta \end{array}\right]}{2(\beta\delta^2-\beta\delta+\beta-1)(\beta\delta+1-\beta)(8\beta\delta^2-7\beta\delta+8\beta-8-\delta)}$ $K^T = \frac{\left[\begin{array}{l} 1-3\delta-2c+2\delta c+c^2+2c\beta-\beta+3\beta\delta-4\beta\delta c \\ -3\beta\delta^2-c^2\beta+2\beta\delta^2 c+\beta c^2\delta+\beta\delta^3+3\delta^2-\delta^3 \end{array}\right]}{2\beta(\beta\delta+1-\beta)(\delta-1)}$ $\pi^T = \frac{\left[\begin{array}{l} 1-2\beta^2\delta^2 c-\delta-\beta^2 c^2\delta-\beta^2\delta^3-2\beta+\beta^2+3\beta^2\delta^2-3\beta^2\delta+2\delta c+5\beta\delta+\beta\delta^3 \\ -4\beta\delta^2-2c+\beta c^2\delta-6\beta\delta c-2c\beta^2+2\beta\delta^2 c+4c\beta-2\beta c^2+\beta^2 c^2+4c\beta^2\delta+c^2 \end{array}\right]}{4(\beta\delta+1-\beta)(1-\delta)}-\frac{K}{2}\beta^2$

4.2. Outsourced Remanufacturing (Model T)

In Model T, the OEM outsources the remanufacturing business to an independent third-party remanufacturer but still undertakes public education. Then, the sequence of events is as follows: In the first stage, the OEM decides whether to invest in public education on green consumption behavior. In the second stage, the OEM determines the remanufacturing authorization fee f to be paid to the third-party remanufacturer. Then, both the OEM and the third-party remanufacturer simultaneously decide on the optimal prices p_n and p_r for new products and remanufactured products, respectively.

Therefore, we can write the problems for the OEM and the third-party remanufacturer as follows:

$$\begin{array}{l} \pi^T = (p_n - c_n)q_n + (f - c_r)q - \frac{K}{2}\beta^2 \\ \Pi^T = (p_r - f)q_r \end{array} \tag{4}$$

The first term in the first equation represents the OEM's profits obtained from selling new products, while the second term represents the OEM's profits obtained from remanufacturing outsourcing. $\frac{K}{2}\beta^2$ represents the cost of investing in public education on green consumption behavior. It should be noted that the presence of the third-party remanufacturer results in the OEM losing its monopolistic position. Then, as the second equation shows, the third-party's profit equals the revenue from selling remanufactured products of $p_r q_r$ minus the remanufacturing outsourcing fee of $f q_r$ charged by the OEM. Furthermore, given that green consumers only purchase remanufactured products, the equilibrium outcomes change. Using backward induction again, we summarize the equilibrium outcomes in Table 1 (detailed proof can be found in Appendix A).

5. Analysis and Insights

The previous two sections provided equilibrium results. We can now compare the differences between models O and T in terms of optimal prices for new/remanufactured products, economic performance, environmental sustainability, and innovation incentives.

Note that, similar to [34], there is a threshold cost K^o in Table 2, below which the OEM engages in public education on green consumption behavior in the first stage. We then compare the difference in the incentive for public education on green consumption behavior in the following proposition (detailed proof can be found in Appendix B).

Proposition 1. *Compared to that in Model T, the OEM has a higher incentive to invest in public education on green consumption behavior in Model O, i.e.,* $K^O > K^T$*.*

It should be noted that investing in public education on green consumption behavior can increase the proportion of the consumer population with green preferences. However, when the remanufacturing is outsourced, the remanufacturing business is the only source for the third-party remanufacturer. Using the parameters K^o and K^T in the Y axis, and the parameter β in the X axis, we can illustrate the difference in the incentive to invest in public education on green consumption behavior in both models. As shown in Figure 2, we can conclude that as the proportion of the consumer population β increases, the incentives for consumer education decrease. This is quite intuitive: the higher proportion of the consumer population β, the less significant are barriers to purchasing remanufactured products. As such, as the proportion of the consumer population β increases, whether in Model O or Model T, the OEM is less likely to invest in public education on green consumption behavior.

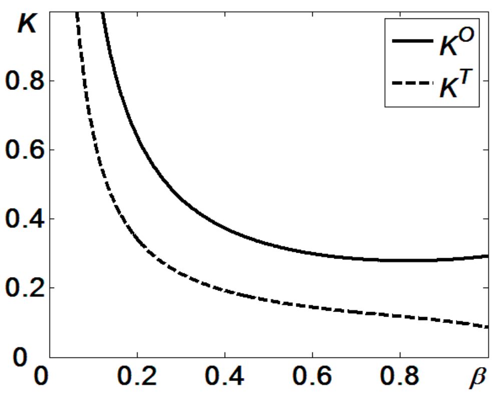


Figure 2. The impacts of β on K ($c = 0.5$ and $\delta = 0.4$).

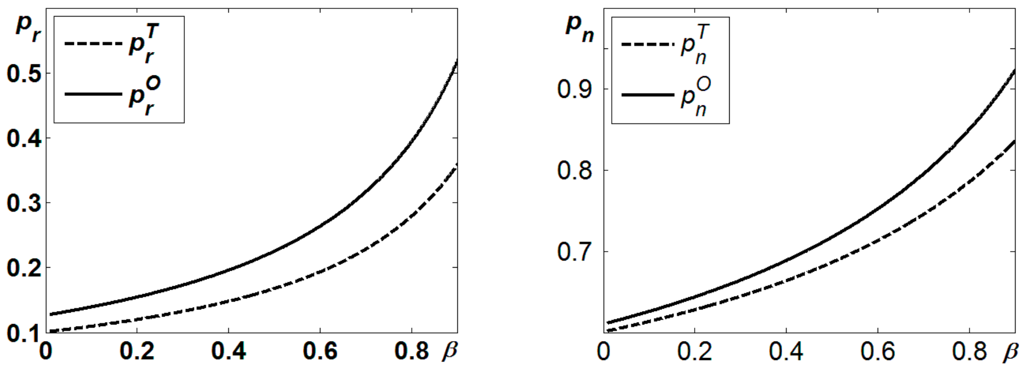
However, based Figure 2, we can further conclude that for any given value of β, $K^O > K^T$, which means that although the increased proportion of the green consumer population in Model T allows the third-party remanufacturer to sell more units of remanufactured products to the green consumers at higher prices, the increase in the proportion of the consumer population cannot effectively limit the cannibalization from the third-party remanufacturer. In contrast, when the OEM undertakes remanufacturing in-house, i.e., Model O, investing in public education on green consumption behavior allows the OEM to directly obtain higher profits from selling remanufactured products to the green consumers. Then, the incentive of K^O is higher than that of K^T.

Proposition 1 indicates that the OEM has a higher incentive to invest in public education on green consumption behavior in Model O, raising the key question: does the higher incentive to invest in public education on green consumption behavior result in a higher margin for the remanufactured products? We first summarize the difference in the optimal prices of of both models in the following proposition (detailed proof can be found in Appendix C).

Proposition 2. *The optimal prices of new (remanufactured) products in Model O are always higher than those in Model T, i.e.,* $p_n^O > p_n^T$ $(p_r^O > p_r^T)$*.*

Note that, using the parameters p_r and p_n in the Y axis, and the parameter β in the X axis, we can see that the difference in the prices of both models depends on the proportion of the consumer population β. More specifically, on the one hand, Proposition 2 reveals that as the proportion of the consumer population β increases, whether in Model O or Model T, the price for the remanufactured products increases. This finding is similar to those of Khor and Hazen [4] and Tully and Winer [9] that in the remanufacturing industry, successful consumer education on green consumption can increase the willingness to pay for the remanufactured products. On the other hand, we confirm that the cannibalization effects between remanufactured and new products play important roles for the OEM optimal quantities choice decisions. That is, as found by Zhou, Xiong [6], Proposition 2 identifies that to limit the cannibalization problems from the remanufactured products, the optimal prices of new (remanufactured) products in Model O are always higher than those in Model T.

Proposition 2 can be interpreted as follows: As Proposition 1 shows, the OEM has a higher incentive to invest in public education on green consumption behavior in Model O. This leads to an increase in the proportion of green consumers, who have a higher willingness to pay for the remanufactured products, and results in a higher optimal price for remanufactured products in Model O, i.e., $p_r^O > p_r^T$ (see, Figure 3a). This higher optimal price for remanufactured products leads to a higher price for the new ones, i.e., $p_n^O > p_n^T$, due to there being less canniablization created by the remanufactured products (see, Figure 3b).



(**a**) (**b**)

Figure 3. The impacts of β on p_r and p_n ($\beta = 0.2$ and $\delta = 0.4$): (**a**) variation in p_r, and (**b**) variation in p_n.

In sum, besides confirming the empirical results of Khor and Hazen [4] and Tully and Winer [9], Proposition 2 further shows that to reduce the cannibalization on new product sales, the OEM has a higher incentive to invest in public education on green consumption behavior in Model O to maintain higher prices for remanufactured products, which results in a higher price for the new ones.

Continuing with the comparison of the optimal outcomes in both models, we summarize the difference in economic performance as follows (detailed proof can be found in Appendix D).

Proposition 3. *The OEM's profits in Model O are always higher than those in Model T, that is,* $\pi^O > \pi^T$*.*

In model O, the OEM dominates both the new product and remanufactured product markets, while in model T, only new products are produced by the OEM, and remanufactured products are produced by a third-party remanufacturer. Therefore, the OEM is a monopolist in model O, but in model T, it has to face competition from the third-party remanufacturers in the remanufactured product market.

Note that, using the parameter π in the Y axis, and the parameter β in the X axis, we can observe that the difference in the profits of both models depends on the proportion of the consumer population β. That is, on the one hand, although Proposition 3 revealed that in the remanufacturing industry, successful consumer education on green consumption can increase the willingness to pay for the remanufactured products, the consumer education paradox dominates. That is, as the proportion of the consumer population β increases, whether in Model O or Model T, the OEM's profits decreases. In addition, based on Proposition 3, we can further conclude that the intention for the OEM to invest in public education on green consumption behavior in Model O is to obtain higher profits (see, Figure 4) from selling products to the green consumers at higher prices (see, Proposition 2).

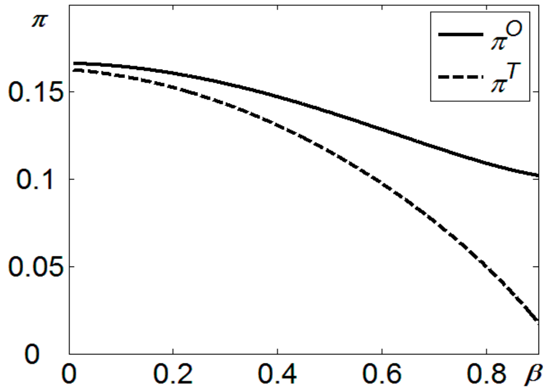


Figure 4. The variation in π with $\beta = 0.2$ and $\delta = 0.4$.

Like Zhang, Chen [35] and Yan, Xiong [27], we model the environmental impacts from the resource-waste perspective. We let i_d represent the environmental impacts of a unit of waste disposal, and adopt e^T and e^O to represent the total environmental impacts for Model T and Model O. Then, we can address the difference in the environmental sustainability of both models as follows (detailed proof can be found in Appendix E).

Proposition 4. *Compared to Model T, the OEM engaging in remanufacturing increases the total environmental impacts, i.e.,* $e^O > e^T$.

Note that, using the parameter e in the Y axis, and the parameter β in the X axis, we can observe that the difference in the sustainability of both models depends on the proportion of the consumer population β. Specifically, on the one hand, we can conclude that as the proportion of the consumer population β increases, whether in Model O or Model T, the environmental impacts decrease. That is, from the sustainability perspective, we can confirm that successful consumer education on green consumption is recognized as an effective method that can help sustainability [4,6]. Proposition 4 also suggests that it is worthwhile for the governments to make efforts on consumer education on green consumption. In addition, Figure 5 further confirms that, rather than considering environmental sustainability, the intention for the OEM to invest in public education on green consumption behavior in Model O is to maintain higher profitability than that in Model T. More specifically, as Proposition 1 shows, the OEM has a higher incentive to invest in public education on green consumption behavior in Model O. This higher incentive is beneficial for the OEM's profitability (see, Proposition 3) but does not, unfortunately, lead to more environmental friendliness.

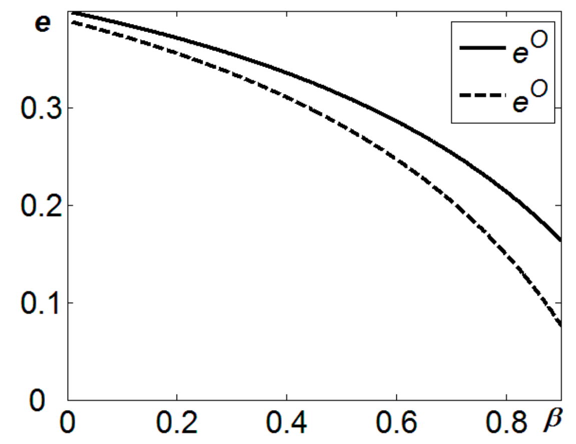


Figure 5. The variation in e with $\beta = 0.2$, $\delta = 0.4$ and $i_d = 0.7$.

Recall that when the remanufacturing is undertaken by a third-party remanufacturer, the remanufacturing business is the only revenue source for the third-party remanufacturer. As such, to maximize profitability, the third-party remanufacturer sells more units of remanufactured products, which results in fewer new products being available, due to the intensified cannibalization effects. As such, outsourcing the remanufacturing business to a third-party remanufacturer is more beneficial for the environment than the OEM engaging in remanufacturing itself.

Thus far, we have analyzed the differences in the prices, economic performance, and environmental sustainability. Finally, we go a further step to examine the role of green consumers and establish the following proposition (detailed proof can be found in Appendix F).

Proposition 5. *(i) The values of $\pi^O - \pi^T$ and $e^O - e^T$ both increase with the increasing proportion β, i.e., $\partial(\pi^O - \pi^T)/\partial\beta > 0$, $\partial(e^O - e^T)/\partial\beta > 0$.*

Proposition 4 indicates that the intention for the OEM to invest in public education on green consumption behavior in Model O is to maintain higher profitability than that in Model T, i.e., $\pi^O > \pi^T$. Proposition 6 further confirms this result: This difference in the economic performance becomes more pronounced as the proportion of green consumers increases, i.e., $\partial(\pi^O - \pi^T)/\partial\beta > 0$. That is, as the proportion of green consumers increases, the increase rate of economic performance in Model O is higher than that in Model T.

Proposition 5 shows that $e^O > e^T$. However, Proposition 6 indicates the difference in the environmental impacts of $\partial(e^O - e^T)/\partial\beta > 0$. In other words, as the proportion of green consumers β increases, the difference in the environmental impacts between Model O and Model T increases. More specifically, based on Proposition 6, we can observe that as the proportion of green consumers β increases, the decrease rate of the environmental impacts in Model O is lower than that in Model T. Therefore, the difference in environmental sustainability increases with the increasing proportion of green consumers.

6. Conclusions

Remanufacturing, recognized as an effective strategy for diverting materials from landfills and fostering sustainability, faces critical barriers such as attitudes, consumer perceptions, and subjective norms that impact the purchase of remanufactured products. In response, consumer education on green consumption has emerged as an effective method to guide consumers in making environmentally conscious choices.

In practice, major brand names, including IBM [36], Apple [37], and Caterpillar [38], actively promote consumer education on green consumption to enhance the OEM's reputation for environmentally friendliness. For instance, Xerox has invested significantly in consumer education to align with corporate sustainability goals focusing on reducing environmental impacts [11].

Although prior analysis has led us to the opinion that environmental concerns truly motivate consumer education, no formal theory has explored how the organizational mode of remanufacturing (in-house or outsourcing) affects consumer education on green consumption. Recognizing the prevalence of both modes in the remanufacturing industry, we aim to develop a theoretical model highlighting manufacturer's incentives for investing in consumer education, considering the choice between in-house or outsourcing remanufacturing.

We now briefly discuss the questions posed at the beginning of the paper.

- How does the organizational mode of remanufacturing, i.e., in-house or outsourcing, affect the manufacturer's incentives in consumer education on green consumption?

Note that the higher the proportion of the consumer population β, the less significant are barriers to purchasing remanufactured products. As such, in Proposition 1, we first observed that as the proportion of the consumer population β increases, whether in Model O or Model T, the OEM is less likely to invest in public education on green consumption behavior. On the other hand, it should be noted that when the remanufacturing is outsourced, the remanufacturing business is the only source for the third-party remanufacturer. Then, Proposition 1 further indicated that, compared to Model T, in Model O, the OEM has a higher incentive to invest in public education on green consumption behavior.

- What effects does an increase in consumer education on green consumption have on decisions, profits, and environmental performance?

On the one hand, we have confirmed the empirical results in Khor and Hazen [4] and Tully and Winer [9]. That is, in the remanufacturing industry, successful consumer education on green consumption can increase the willingness to pay for the remanufactured products. On the other hand, we further identified that to limit the cannibalization problems from the remanufactured products; the optimal prices of new (remanufactured) products in Model O are always higher than those in Model T. Then, in contrast to the common belief that environmental concerns drive consumer education, we demonstrate that such education creates opportunities for opportunistic behaviors impacting profitability and environmental goals. Specifically, a higher incentive for consumer education allows the OEM to maintain higher profit margins from remanufactured units, but it may compromise environmental sustainability due to increased manufacturing of new products.

In sum, we confirm the recent empirical evidence and experimental results (e.g., Khor and Hazen [4], Tully and Winer [9], and Wang, Wang [12]) and have recognized various economic and sustainable benefits for the OEM. However, this paper still calls for governments and regulatory institutions to pay attention to the fact that with flexibility in remanufacturing outsourcing, consumer education on green consumption may induce a consumer education paradox, which may lead to opportunistic behaviors that compromise both profitability and environmental objectives.

Our analysis is built on several strong assumptions, and we now provide several possible directions for future research. Firstly, we assume that environmentally friendly consumers are willing to pay as much for a remanufactured unit as for a new one. While empirical evidence supports the perception that green consumers perceive remanufactured products as more environmentally friendly, exploring the difference in willingness between new and remanufactured products is worth addressing. Secondly, in both models, decisions are made in a single-period scenario, but multi-period settings may better capture dynamic changes in consumer perceptions and attitudes under consumer education. It is suggested that future research should also investigate multi-period scenarios. Thirdly, our analysis highlights the impact of consumer education on the benefit of remanufactured products and the potential negative impact on new products sales. We encourage future researchers to obtain empirical analysis data to verify our main results. We believe that empirical analyses could provide stronger evidence to support or revise the theoretical hypotheses, thereby enhancing the robustness and credibility of the findings.

Author Contributions: Writing—original draft preparation, L.S.; writing—review and editing, Q.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Humanities and Social Sciences Foundation for Young Scholars of China's Ministry of Education (15YJC630154).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Derivation of Equilibrium Outcomes of Both Models

Analysis of the Scenario with In-house Remanufacturing (Model O). In Model O, both new products and remanufactured products are provided by the original equipment manufacturer. Then the OEM's problem is as follows.

$$\max_{p_n,p_r} \pi^O = (p_n - c_n)q_n + (p_r - c_r)q_r - \frac{K}{2}\beta^2$$

By substituting the inverse demand functions of (2) into the above equation, we can obtain the Hessian matrix as follows:

$$H_2 = \begin{vmatrix} \partial^2\pi^O/\partial p_n^2 & \partial^2\pi^O/\partial p_n\partial p_r \\ \partial^2\pi^O/\partial p_r\partial p_n & \partial^2\pi^O/\partial p_r^2 \end{vmatrix} = \begin{vmatrix} \frac{2(1-\beta)}{\delta-1} & \frac{2(1-\beta)}{1-\delta} \\ \frac{2(1-\beta)}{1-\delta} & \frac{2(1-\beta+\beta\delta-\beta\delta^2)}{(\delta-1)\delta} \end{vmatrix}$$

It can be observed that for any $0 < \beta < 1$ and $0 < \delta < 1$, the first-order Hessian matrix is $H_1 < 0$, and the second-order Hessian matrix is $H_2 > 0$. Therefore, there exists an optimal price p_n and p_r that maximize the above equation.

By using the method of first-order partial derivatives, the optimal prices for the original product manufacturer to produce new products and remanufactured products can be obtained as:

$$P_n = \frac{2\beta\delta+1-\beta-\beta\delta^2+\beta\delta c+c-c\beta}{2(\beta\delta+1-\beta)}$$
$$P_r = \frac{\delta}{2(\beta\delta+1-\beta)}$$

Substituting them into the profits, this leads to the OEM's total profit being

$$\pi^O = \frac{\begin{bmatrix} \beta^2\delta^3 - \beta\delta^3 - 3\beta^2\delta^2 + 2\beta^2\delta^2 c - 2\beta\delta^2 c + 4\beta\delta^2 + 3\beta^2\delta \\ -4\beta^2\delta c + \beta^2\delta c^2 - 5\beta\delta + 6\beta\delta c - \beta\delta c^2 - 2c\delta + \delta - \beta^2 \\ -c^2\beta^2 + 2c\beta^2 + 2c^2\beta - 4c\beta + 2\beta - 1 - c^2 + 2c \end{bmatrix}}{4(\beta\delta + 1 - \beta)(-1 + \delta)} - \frac{K}{2}\beta^2$$

Clearly, the profitability decreases in K linearly, and the OEM prefers $\beta > 0$ over $\beta = 0$ if $K < K^O$, where K^O satisfies $\pi^O(\beta > 0) = \pi^O(\beta = 0)$, i.e.,

$$K^O = \frac{\begin{bmatrix} 1 - 3\delta - 2c + 2\delta c + c^2 + 2c\beta - \beta + 3\beta\delta - 4\beta\delta c \\ -3\beta\delta^2 - c^2\beta + 2\beta\delta^2 c + \beta c^2\delta + \beta\delta^3 + 3\delta^2 - \delta^3 \end{bmatrix}}{2\beta(\beta\delta + 1 - \beta)(-1 + \delta)}$$

All equilibrium decisions and profits are presented in Table 1.

Analysis of the Scenario with Outsourced remanufacturing (Model T). In Model T, the OEM outsources the remanufacturing business to an independent third-party remanufacturer, but still undertakes public education. Therefore, we can write the problems for the original equipment manufacturer and the third-party remanufacturer as follows:

$$\begin{array}{l}\pi^T = (p_n - c_n)q_n + (f - c_r)q - \frac{K}{2}\beta^2 \\ \Pi^T = (p_r - f)q_r\end{array}$$

Similar to Model O, by substituting the inverse demand functions of (1) into the above equation, we can obtain

$$p_r = \frac{2f\beta\delta^2 - f\beta\delta - f\delta + 2f\beta - \delta - 2f + \beta\delta c + \beta\delta^2 - \delta c + \delta^2 - \beta\delta}{4\beta + 4\beta\delta^2 - 4 + \delta - 5\beta\delta}$$

$$p_n = \frac{\left[\begin{array}{l} 2\beta\delta^2 c - 2 + 3f\beta\delta^2 - 3f\beta\delta + 2c\beta - 2c - 5\beta\delta \\ +3f\beta - 2\beta\delta^3 + 2\delta - 3f - 2\beta\delta c + 2\beta + 5\beta\delta^2 \end{array}\right]}{4\beta + 4\beta\delta^2 - 4 + \delta - 5\beta\delta}$$

Substituting them into the profits, this leads to the OEM's total profit. Maximizing it with f, we can then obtain

$$f = \frac{\delta\left[\begin{array}{l} \beta^3\delta c - \beta^3\delta^2 c - 14\beta^2\delta^3 - 13\beta^2\delta + 20\beta^2\delta^2 \\ -\beta\delta^2 c + 2\beta^3\delta^2 + 8 + 3\beta\delta c - \beta^3\delta^3 - \beta^3\delta \\ -\beta\delta^3 + 2\beta^2\delta^2 c + 13\beta\delta - 3\beta^2\delta c + 8\beta^2 \\ +8\beta^2\delta^4 - \delta c - 14\beta\delta^2 + \delta - 16\beta \end{array}\right]}{2(\beta\delta^2 - \beta\delta + \beta - 1)(\beta\delta + 1 - \beta)(8\beta\delta^2 - 7\beta\delta + 8\beta - 8 - \delta)}$$

Solving $\pi^O(\beta > 0) = \pi^O(\beta = 0)$ provides

$$K^O = \frac{\left[\begin{array}{l} 1 - 3\delta - 2c + 2\delta c + c^2 + 2c\beta - \beta + 3\beta\delta - 4\beta\delta c \\ -3\beta\delta^2 - c^2\beta + 2\beta\delta^2 c + \beta c^2\delta + \beta\delta^3 + 3\delta^2 - \delta^3 \end{array}\right]}{2\beta(\beta\delta + 1 - \beta)(-1 + \delta)}$$

All equilibrium decisions and profits are again summarized in Table 1. It should be noted that to ensure all equilibrium decisions are positive, we need $c < \frac{(1-\delta)(1-2\beta)}{2(1-\beta)}$.

Appendix B. Proof for Proposition 1

Based on the outcomes in Table 1, we can obtain

$$K^T - K^O = \frac{\left[\begin{array}{l} 21\beta^2\delta^4 - 20\beta^2 c^2\delta - 74\beta^2\delta^3 - 32\beta + 32\beta^2 + 29\beta^2 c^2\delta^2 \\ +101\beta^2\delta^2 - 15\delta^2 c^2 + 128\beta c - 84\beta^2\delta - 24\beta c^2\delta - 10\beta\delta^3 \\ +22\delta^2 c + 52\beta\delta - \beta\delta^4 - 8\beta\delta^4 c - 15\delta^3 c^2 + 40\delta c + 4\beta^2 c^2\delta^3 \\ -45\beta c^2\delta^3 + 17\beta\delta^4 c^2 - 52\beta\delta^3 c - 9\beta\delta^2 - 64c + 32c^2 \\ +104\beta^2 c\delta + 18\beta c^2\delta^2 - \delta^4 c^2 + 4\beta^2\delta^5 - 98\beta^2\delta^2 c \\ -64\beta c^2 + 50\beta^2\delta^3 c - 144\beta\delta c + 8\beta\delta^5 c^2 + 44\delta c^2 + 8\beta^2\delta^4 c \\ +76\beta\delta^2 c - 64\beta^2 c + 2\delta^3 c + 32\beta^2 c^2 \end{array}\right]\delta}{2(8 + \delta)(\beta\delta^2 - \beta\delta + \beta - 1)(8\beta\delta^2 - 7\beta\delta + 8\beta - 8 - \delta)(1 - \delta)\beta}$$

For any $0 < \beta < 1$, $0 < \delta < 1$, we find that $K^T - K^O < 0$ depends on the numerator of the above equation. In particular, the function is concave in factor c. Solving the equation, we can find that for any $c < \frac{(1-\delta)(1-2\beta)}{2(1-\beta)}$, $K^T - K^O < 0$ is always true. Then we can conclude that the original equipment manufacturer has a higher incentive to invest in public education on green consumption behavior in Model O, i.e., $K^O > K^T$.

Appendix C. Proof for Proposition 2

To prove $p_n^O > p_n^T$, we have to show that $\frac{(c-\beta\delta+\beta-\beta c)\delta}{8\beta\delta^2-7\beta\delta+8\beta-8-\delta} < 0$. After simplification, we find that for any $0 < \beta < 1$, $0 < \delta < 1$, $c < \frac{(1-\delta)(1-2\beta)}{2(1-\beta)}$, the above equation is always negative. As such, we can conclude that $p_n^O > p_n^T$.

To prove $p_r^O > p_r^T$, we have to show that $\frac{(c-\beta\delta+\beta-\beta c)(4\beta-3\beta\delta+4\beta\delta^2-4-\delta)\delta}{2(8\beta\delta^2-7\beta\delta+8\beta-8-\delta)(\beta\delta^2-\beta\delta+\beta-1)} < 0$. After simplification, we find that for any $0 < \beta < 1$, $0 < \delta < 1$, $c < \frac{(1-\delta)(1-2\beta)}{2(1-\beta)}$, the above equation is always negative. As such, we can conclude that.

Appendix D. Proof for Proposition 3

To prove $\pi^O > \pi^T$, we have to show that $\frac{(c-\beta\delta+\beta-\beta c)^2(4+\delta-4\beta+3\beta\delta-4\beta\delta^2)\delta}{(\beta\delta^2-\beta\delta+\beta-1)(8\beta\delta^2-7\beta\delta+8\beta-8-\delta)(1-\delta)} < 0$. After simplification, we find that for any $0 < \beta < 1$, $0 < \delta < 1$, $c < \frac{(1-\delta)(1-2\beta)}{2(1-\beta)}$, the above equation is always negative. As such, we can conclude that $\pi^O > \pi^T$.

Appendix E. Proof for Proposition 4

Comparing the total disposal impact between Model T and Model O. We obtain $e^O - e^T = \frac{(\beta\delta-\beta+\beta c-c)i_d\begin{bmatrix} 6\beta\delta-\beta\delta^3+\delta+\delta^2-7\beta^2\delta+12\beta^2\delta^2 \\ -7\beta^2\delta^3+4\beta^2-8\beta+4\beta^2\delta^4-9\beta\delta^2+4 \end{bmatrix}}{2(\beta\delta^2-\beta\delta+\beta-1)(8\beta\delta^2-7\beta\delta+8\beta-8-\delta)(-1+\delta)}$. After simplification, we find that for any $0 < \beta < 1$, $0 < \delta < 1$, $c < \frac{(1-\delta)(1-2\beta)}{2(1-\beta)}$, the above equation is always negative. As such, we can conclude that $e^O > e^T$.

Appendix F. Proof for Proposition 5

Based on the function of $\pi^O - \pi^T$ in Proposition 3, we can obtain

$$\partial(\pi^O-\pi^T)/\partial\beta = \frac{(\beta\delta-\beta+c\beta-c)\delta\begin{bmatrix} 128-80\delta-352\beta-32\beta^2\delta^6+320\beta^2 \\ -4\delta^3-1280\beta^2\delta^3+572\beta\delta-503\beta\delta^2 \\ -44\delta^2-96\beta^3+96\beta^3\delta^7+3\beta\delta^5 \\ -348\beta^3\delta^6-759\beta^3\delta^2+206\beta\delta^3 \\ +1338\beta^2\delta^2+13\delta^2c+348\beta^3\delta \\ -840\beta^2\delta+74\beta\delta^4+724\beta^2\delta^4-16\delta^5c\beta \\ +759\beta^3\delta^5+96c\beta^3-1074\beta^3\delta^4+\delta^4c \\ -230\beta^2\delta^5+1074\beta^3\delta^3-96c-68\delta c \\ -288c\beta^2-93\beta^2\delta^4c+273\beta^2\delta^3c \\ +15\delta^3c+436c\beta^2\delta-649c\beta^2\delta^2 \\ +151\delta^3c\beta+129\beta\delta^2c-116\beta\delta c \\ +96\beta^3\delta^6c-252c\beta^3\delta+507c\beta^3\delta^2 \\ +507\beta^3\delta^4c-116\beta^2\delta^5c-252\beta^3\delta^5c \\ -31\delta^4c\beta-567\beta^3\delta^3c+288c\beta+32\delta^6c\beta^2 \end{bmatrix}}{4(\beta\delta^2-\beta\delta-1+\beta)^2(8\beta\delta^2-7\beta\delta-\delta+8\beta-8)^2(-1+\delta)}$$

Solving this function, we can determine that for any $0 < \beta < 1$, $0 < \delta < 1$, $c < \frac{(1-\delta)(1-2\beta)}{2(1-\beta)}$, the above equation is always positive. As such, we can conclude that $\partial(\pi^O - \pi^T)/\partial\beta > 0$.

Based on the function of $e^O - e^T$ in Proposition 4, we can obtain

$$\partial(e^O - e^T)/\partial\beta = \frac{\begin{bmatrix} -32 + 50\beta^2\delta^6 + 20\delta + 128\beta + 8\delta^3 + \delta^4 + 802\beta^2\delta^3 + 32c \\ -208\beta\delta - 15\delta^4 c + 212\beta\delta^2 + 192\beta^2 c - 192\beta^2 + 3\delta^2 - 128\beta c \\ +32\beta^4 c - 128\beta^3 c + 534\beta^2\delta^2 c + 16\delta^6 c\beta + 80\beta\delta c - 50\beta\delta^3 c \\ +139\beta^2\delta^4 c - 312\beta^2 c\delta + 28\beta\delta^4 c + 54\beta^2\delta^5 c - 140\beta\delta^2 c + 13\delta^2 c \\ +12\delta c + 13\delta^3 c - 148\beta^4\delta^8 + 32\beta^4\delta^9 - 22\delta^5 c\beta - 268\beta^2\delta^3 c - 11\beta^2\delta^6 c \\ -670\beta^3\delta^4 c + 762\beta^3\delta^3 c - 700\beta^3\delta^2 c - 4\delta^7 c\beta^2 - 106\beta^3\delta^6 c + 298\beta^3\delta^5 c \\ +336\beta^3 c\delta - 8\beta^3\delta^7 c + 550\beta^4\delta^4 c - 457\beta^4\delta^3 c + 293\beta^4\delta^2 c + 293\beta^4\delta^6 c \\ -457\beta^4\delta^5 c - 116\beta^4 c\delta - 116\beta^4\delta^7 c + 32\beta^4\delta^8 c + 128\beta^3 - \delta^5 c - 98\beta^3\delta^7 \\ -1007\beta^4\delta^4 - 750\beta^4\delta^6 - 8\delta^8\beta^3 + 750\beta^4\delta^3 - 409\beta^4\delta^2 + 1007\beta^4\delta^5 \\ -2\beta\delta^5 + 404\beta^3\delta^6 + 1036\beta^3\delta^2 - 98\beta\delta^3 - 842\beta^2\delta^2 - 464\beta^3\delta \\ +504\beta^2\delta - 32\beta\delta^4 - 422\beta^2\delta^4 - 7\beta^2\delta^7 - 968\beta^3\delta^5 + 1432\beta^3\delta^4 \\ +107\beta^2\delta^5 - 32\beta^4 + 148\beta^4\delta - 1462\beta^3\delta^3 + 409\beta^4\delta^7 \end{bmatrix}}{2(\beta\delta^2 - \beta\delta + \beta - 1)^2(8\beta\delta^2 - 7\beta\delta + 8\beta - 8 - \delta)^2(1-\delta)}$$

After simplification, we find that for any $0 < \beta < 1, 0 < \delta < 1, c < \frac{(1-\delta)(1-2\beta)}{2(1-\beta)}$, the above equation is always positive. As such, we can conclude that $\partial(e^O - e^T)/\partial\beta > 0$.

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