The Effect of Introducing Upgraded Remanufacturing Strategy on OEM’s Decision

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Abstract: Although remanufacturing has great economic and environmental potential, internal cannibalization, and lack of consumer acceptance of remanufactured products prevent original equipment manufacturer (OEM) from realizing the full potential value through remanufacturing. Practices show that remanufactured products can realize their value by the donation, besides resale. Thus, this paper incorporates the donation of remanufactured products with government subsidy and presents an upgraded remanufacturing strategy to expand the demand for remanufactured products and weaken the internal cannibalization of remanufactured products. We respectively construct the two-period game model with and without upgraded remanufacturing and explore the effect of upgraded remanufacturing on production decision, economic and environmental benefits. The main conclusions are as follows. The donation subsidy is negatively related with the sale quantity of remanufactured products, but is positively related with the donation quantity of remanufactured products and the quantity of new products. The donation subsidy expands the demand for remanufactured products and weakens internal cannibalization of remanufactured products. Whether the upgraded remanufacturing strategy is profitable depends on the fixed cost of the remanufacturing. When consumers consider remanufactured products environmentally friendly, the government can realize an OEM’s win-win situation where the economic and environmental benefits get improved by adjusting the donation subsidy. Otherwise, introducing upgraded remanufacturing makes the environment worse. Comparatively speaking, a low-cost and environmentally friendly manufacturer is relatively easier to achieve the win-win situation through donation subsidy.

Keywords: closed-loop supply chain; corporate social responsibility; upgraded remanufacturing; charitable donation

1. Introduction

The advancement of productivity and the progress of society bring plentiful products, meanwhile result in a lot of end of life (EOL) products, especially waste electrical and electronic equipment (WEEE). From the perspective of quantity and environmental impact, WEEE becomes the world’s fastest growing waste stream [1]. According to statistics, the amount of WEEE around the world reached 41.8 million tons in 2014 [2]. It is growing at a rate of 3–5% each year and it is estimated to reach 50 million tons in 2018 [2]. The treatment of EOL products has become a major problem that troubles the sustainable development in the world. Thus, it is worth to study how to reduce EOL
products as much as possible, transfer the landfill and incineration of EOL products, and improve the economic and environmental benefits.

Classic supply chain, also called forward supply chain, only focuses on optimizing the production, transport, sale of products but does not assume any liability for EOL products [3]. To achieve the better environmental benefit, more and more governments promulgate environmental regulations to force manufacturers to collect EOL products. Therefore, the closed-loop supply chain (CLSC) that combines the forward and the reverse supply chain has attracted people’s attention. Guide and Van Wassenhove [4] point out that CLSC is a revenue opportunity for manufacturers, and is defined as “the design, control and operation of a system to maximize value creation over the entire life cycle of a product and recover dynamic value from different types and volumes of returns over time” from the business perspective. Based on the framework of CLSC, the manufacturer not only sells products through the forward supply chain, but also collects EOL products through the reverse supply chain [5].

The collected EOL products can recover their value through repairing, disassembling, recycling and remanufacturing. Remanufacturing is considered as the most effective and environmentally friendly way of recovering the value [6]. When compared with manufacturing new pump, the remanufactured equipment brings a reduction of 60% in energy consumption, 75% in waste and 70% in carbon emissions [7]. More and more enterprises, such as BMW, IBM, DEC and Xerox, gain profits by remanufacturing EOL products [8]. But, Orsdemir et al. [9] point out that many enterprises still do not choose to remanufacture, mainly because of internal cannibalization and cost. Internal cannibalization means the market demand for new products is encroached by remanufactured products. Thus, our first main research objective is how to weaken the cannibalization effect of remanufactured products.

Although remanufactured product has the same quality and function as new product does, consumers do not have enough recognitions of remanufactured product [10]. Ferguson and Toktay [11] point out that the reason for the lower relative willingness-to-pay to remanufactured products is either due to customer concerns about quality or because of a ‘fair price’ perspective—if it costs less for the manufacturer to remanufacture the product than to make it, then the customer wants that reflected in the price. Thus, fair price and loss aversion hinder the increase in demand for remanufactured products [12,13]. Thus, our second main research objective is to how to expand the demand for remanufactured products.

In a global business world, corporate social responsibility (CSR) requires enterprises not only to achieve profits but also to assume corresponding social responsibility. CSR largely affects consumers’ decisions and consumers are willing to pay higher prices for products manufactured by corporates implementing CSR [14]. Charitable giving is a kind of pro-social behavior and is considered as an important part of CSR [15]. But in essence, it is a kind of strategic gift that is related to business profits. Enterprises can build good images and improve brand reputations, forming an intangible competence [16]. According to a survey report by the Conference Board, a New York business research think tank, more than half of all the charitable contributions by United States (U.S.) companies were merchandise, including pharmaceuticals, medical supplies, clothing, printers, and computers [17]. Hewlett-Packard Co. (Palo Alto, CA, USA), in its 2004 fiscal year, donated $45 million in products [17]. When compared with new products, remanufactured products have the same qualities and functions, but their prices are lower than 30–40% of that of new products and their costs are only 40–65% of costs of new products [18]. Therefore, low-cost and high-quality remanufactured products are more suitable for donations. In September 2013, National Development and Reform Commission (NDRC) hosted “Beijing-Tibet trip” with respect to remanufacturing, and some enterprises, such as China National Heavy Duty Truck Group Co. Ltd. (Jinan, China) and China Shandong Forever Co. Ltd. (Jinan, China), gave publicity to remanufacturing and donated remanufactured products to Tibet Autonomous Region, winning the support and recognition from the society (http://hzs.ndrc.gov.cn/newjsjyxs/201310/20131010_561716.html). Hence, this paper takes charitable donation as another strategy of realizing the value of remanufactured products.
The charitable donation improves social welfare and eases the pressure on governments, thus all the governments around the world encourage enterprises to implement charitable donations [19]. Governmental efforts to direct business behavior toward certain socially desirable outcomes take a variety of forms [20]. One common motivation is to provide subsidies, including direct or indirect subsidies, for activities that are consistent with policy objectives. In the United States, the 1976 tax provision by Congress allows big companies to avail up to twice the tax deduction they normally receive if they donate goods to charity instead of discarding them [20]. Recently, Chapter IX of China’s new Charity Law allows for charitable donations to be deducted from taxable income (http://www.chinalawtranslate.com/2016charitylaw/?lang=en). Arya and Mitterndorf [20] put forward a direct subsidy for product donation and demonstrate that it has the same legislative efficiency as the indirect subsidy (the tax deduction) does. It is necessary to design an incentive policy that incorporates the donation to realize the value of remanufactured products. The government can/must play in the promotion of remanufactured products [21]. Thus, our last main research objective is to explore the effect of donation subsidy on the economy and environment.

Our aforesaid objectives translate into the following research questions: (1) under the upgraded remanufacturing strategy, what is the effective condition where both the donation and sale of remanufactured products coexist? (2) Under the upgraded remanufacturing strategy, how does the donation subsidy affect the production decision of the original equipment manufacturer (OEM)? (3) Compared with the strategy without remanufacturing, how are the environmental and economic benefits of the OEM under the upgraded remanufacturing strategy? Are there any Pareto improvements of win-win of economic and environment?

To solve these questions, we introduce the donation of remanufactured products with government subsidy and develop a two-period model of internal competition between new and remanufactured products to analyze a monopolist’s production decisions. In line with the technology roadmap (see Figure 1), we explore two different strategies of the monopolist: (1) the absence of remanufacturing; and (2) the presence of remanufacturing. The former is a benchmark, where the OEM only produces and sells new products in two periods. For the latter, the OEM produces and sells new products in the first period. In the second period, the OEM collects and remanufactures the cores besides producing and selling new products. As the government provides the donation subsidy for remanufactured products, the OEM simultaneously sells and donates them. For the latter, we compare the different cases: (1) the donation subsidy is effective; and, (2) the donation subsidy is invalid, and analyze the effect of the subsidy on expanding the demand for remanufactured products and weakening internal cannibalization. Then we compare production decision, economic profit and environmental impact of two different strategies and analyze the impact of incorporating upgraded remanufacturing strategy on production decision, economic profit, and environmental impact.

![Figure 1. Technology Roadmap.](image-url)
The remainder of this paper is organized as follows. Section 2 reviews the related literature. Section 3 summarizes research questions, research hypotheses, and symbols description in detail. Section 4 presents two stylized models to describe research questions and solves the optimal solution of the OEM. Section 5 compares and analyzes the effect of introducing upgraded remanufacturing strategy on production decision, economic profit, and environmental impact. Section 6 presents some numerical examples to verify the findings and discovers new results. Section 7 summarizes the main conclusions. All of the proofs are provided in Appendix A.

2. Literature Review

Studies that are related to this paper mainly focus on five aspects: sustainable supply chain, closed-loop supply chain, remanufacturing, corporate social responsibility, and government incentive. Manufacturing industry has fundamentally changed and OEM focuses on core competences, supply chain configurations and environmental benefits in the supply chain [22,23]. Increasing resource scarcity, which leads to rising resource prices and price volatility, has a negative impact on firms and supply chain [24]. Thus, the interdisciplinary research on supply chains and sustainability, namely sustainable supply chain, has received extensive attention [25]. Centobelli et al. [26] review 122 papers with respect to energy-efficient and sustainable supply chain management using descriptive content analysis and present that more than 50% of literature use quantitative methodologies. Pourhejazy and Kwon [27] summarize quantitative methodologies with respect to supply chain network, in particular integrated mathematical modeling and simulation-optimization frameworks. Centobelli et al. [28] identify a taxonomy that is used by logistics service providers to achieve their environmental sustainability strategies from the perspectives of green aims, green practices and technological tools. Masi et al. [24] show that the circular economy creates synergies between environmental and economic development goals and reshapes competitive priorities for firms and supply chains. As an OEM manufacturing strategy, sustainable supply chain must be integrated into the overall corporate strategy and has a profound impact on corporate performance [29].

The pressure from environment deterioration and resource shortage emphasizes the importance of the closed-loop supply chain management. Guide and Van Wassenhove [30] provide a basic framework for CLSC and classify its strategies, tactics, and operations. Many scholars focus on the sale and collection of CLSC. Savaskan et al. [31] regard it the most effective that retailers are responsible for collecting EOL products. Atasu et al. [32] investigate the impact of collection cost structures on manufacturers’ decision making of the best reverse channel. Many researchers study the pricing decisions of new products and remanufactured products in CLSC management. Ferrer and Swaminathan [33] study the optimal prices and quantities for monopolist and oligopolist in two-period, multi-periods, and infinite periods. Changes in the structure of supply chain also influence the operating efficiency of EPR system. Maiti and Giri [34] study three different Stackelberg game models led by the manufacturer, the retailer and the third party in centralized, decentralized, and Nash scenarios. This paper regards CLSC as the framework and assumes that the integrated monopolist is responsible for selling new and remanufactured products and collecting EOL products in two periods simultaneously.

Remanufacturing, as a market competition, has attracted more and more enterprises’ attention. Many scholars especially emphasize the competitive remanufacturing and cannibalization of remanufacturing. Atasu et al. [35] consider that remanufacturing can be used to deal with market competition. Ferguson and Toktay [11] consider two-period and remanufacturing constraints and investigate the effect of introducing remanufacturing strategy on operations management. Yenipazarli [36] characterizes the condition where the manufacturer achieves an economic and environmental ‘win-win’ situation by remanufacturing under emissions regulation. The above literature reviews only take resale as the way of realizing the value of remanufactured products and do not take the donation of remanufactured products into account. Also, cannibalization has not been paid much attention.
There have been a lot of literature reviews about the application of CSR in the supply chain in the past ten years. Ni et al. [37] investigate the allocation of social responsibility in the two-echelon supply chain and design the coordination mechanism of the wholesale price to share the responsibility cost among members. Ni and Li [38] explore the interaction of CSR between a supplier and a manufacturer and emphasize the impact of individual CSR cost on the channel members. This paper investigates the interdisciplinary research on the charitable donation of CSR and CLSC. The charitable donation is an important embodiment of CSR [39]. Wang et al. [40] investigate the relationships of CSR, brand equity, and firm performance and find that brand equity and CSR have significant positive correlations with the firm performance. Long and Hu [41] present that non-monetary asset donations are important as they bring goods and materials to areas where they are desperately needed. Jia and Zhang [16] find that the firm that takes active participation in charitable donations can acquire more bank loans and government subsidy. Particularly, enterprises in China are used to establish a good political relationship with the government by charitable donations. Arya and Mittendorf [20] explore the interactions with suppliers, manufacturers and retailers when manufacturers implement charitable donations and analyze the significant impact of the government subsidy on the channel members. The above literature reviews only take the donation of new product into account. We focus on the interdisciplinary research on remanufactured product and the charitable donation.

It is important for the government to encourage and support the remanufacturing of enterprises. The current main forms of government incentive are subsidy and tax rebate. Shu et al. [42] compare remanufacturing subsidy and carbon tax rebate and find that rebate has more influence on pricing. Liu et al. [43] investigate the trade-off between remanufacturing and recycling EOL products with the government subsidy. The above literature reviews only study the resale of remanufactured products with subsidy and do not take the donation of remanufactured products into account. Zhu et al. [44] put forward two incentive policies to subsidize the resale and donation of remanufactured products respectively and provide the basis for choosing the government subsidy policy from the perspective of social welfare. Although Zhu et al. [44] consider the donation of remanufactured products, they do not take the remanufacturing constraints and multiple periods into account. Arya and Mittendorf [20] study the impacts of the donation subsidy on suppliers, manufacturers, and retailers, and suggest that direct donation subsidy and indirect tax breaks have the same incentive effects. Instead, this paper incorporates the donation of remanufactured products into CLSC and considers the two-period and remanufacturing constraints.

Table 1 shows that the comparison between related literature and our paper by research content and methodology. 10 papers selected focus on life cycle including six papers concern single-period, three papers concern multi-period, and one paper concerns single-period and multi-period; 10 papers selected focus on remanufacturing. Four papers selected focus on product donation under government subsidy, including three papers concern donation of new products and one paper concerns donation of remanufactured products. Seven papers selected focus on environment, including three review papers that provide a comprehensive overview on sustainable supply chain and four papers which concern environmental impact by quantitative methods. 13 papers selected focus on economic performance, including 11 papers that concern profits by game theory.
Table 1. Comparison between related literature and our paper.

| Authors, Year | Life Cycle | Remanufacturing | Donation | Economy | Environment | Methodology |
|---------------|------------|-----------------|----------|---------|-------------|-------------|
|               | Single-Period | Multi-Period | New Products | Remanufactured Products |              |             |
| Centobelli et al., 2018 [26] | ● | ● | ● | ● | Literature review |
| Centobelli et al., 2017 [27] | ● | ● | ● | ● | Literature review |
| Masi et al., 2017 [34] | ● | ● | ● | ● | Literature review |
| Guide and Van Wassenhove, 2006 [30] | ● | ● | ● | ● | Literature review |
| Savaskan et al., 2004 [31] | ● | ● | ● | ● | Literature review |
| Ferrer and Swaminathan, 2010 [33] | ● | ● | ● | ● | Game theory |
| Maiti and Giri, 2015 [34] | ● | ● | ● | ● | Game theory |
| Atasu et al., 2008 [35] | ● | ● | ● | ● | Game theory |
| Ferguson and Toktay, 2006 [29] | ● | ● | ● | ● | Game theory |
| Yenipazari, 2016 [36] | ● | ● | ● | ● | Stackelberg game |
| Long and Hu, 2013 [41] | ● | ● | ● | ● | Case study |
| Jia and Zhang, 2016 [41] | ● | ● | ● | ● | Statistical analysis |
| Arya and Mittendorf, 2015 [20] | ● | ● | ● | ● | Stackelberg game |
| Shu et al., 2017 [42] | ● | ● | ● | ● | Static game |
| Liu et al., 2017 [43] | ● | ● | ● | ● | Static game |
| Zhu et al., 2017 [44] | ● | ● | ● | ● | Stackelberg game |
| Our paper | ● | ● | ● | ● | Dynamic programming |
Our work differs from the above studies for the following reasons: (1) This paper emphasizes a new way to realize the value of remanufactured products, namely charitable giving. The donation of remanufactured products is driven by donation subsidy. We design a direct subsidy mechanism instead of tax breaks, which expands the demand for remanufactured products and weakens the internal cannibalization. Meanwhile, we take the supply constraint of EOL products in account. Remanufactured products in second period can be used not only for sales, but also donations, namely upgraded remanufacturing strategy. (2) Because the manufacturer first determines the first-period production decision, then determines the second-period production decision. We model a two-period model to capture the dynamic aspects of the CLSC and donation subsidy, which is dynamic programming problem. Unlike the game theory, optimization involves just one decision maker, who chooses what to do at each point of time. (3) Besides analyzing the economic profit, we particularly underline the environmental impact of the manufacturer after adopting the upgraded remanufacturing strategy. We selected total carbon emissions as the environmental assessment indicator, which is recognized worldwide as a measure of environmental impact.

3. Problem Description and Symbols

This section mainly introduces relevant assumptions and symbols of two-period production decisions of the manufacturer with or without remanufacturing. The strategy without remanufacturing is the benchmark model, which is denoted by superscript $N$. The strategy with remanufacturing is denoted by superscript $D$.

With respect to two periods, a new product purchased in the first period cannot provide positive utility for the customers in the second period. Thus, the product has a useful life time of only one sale period. This assumption means that the consumers’ purchasing behaviors across the two periods are independent [33,36,45]. Under the strategy $N$, the manufacturer only produces new products in the first and second periods, and the decisions of two periods are independent. Under the strategy $D$, the manufacturer assumes the responsibility for collecting and remanufacturing used products, and the value of remanufactured products can be realized by resale and donation. At the moment, the manufacturer produces new products in the first period. The used products must be remanufactured at the end of their life and then reused. Only fraction of used products at the end of the first period can be collected and remanufactured. Thus, the collection rate is denoted as $\rho$, $\rho \in (0, 1)$ [9]. In the second period, new products and remanufactured products are sold simultaneously. The price and production quantity of new products in the first period are $p_1$ and $q_1$, and the inverse demand function of the new product in the first period is $p_1 = 1 - q_1$ [36]. The price and production quantity of new products in the second period are $p_2$ and $q_2$, respectively. In addition, the price and production quantity of the remanufactured product are $p_r$ and $q_r$, respectively. Similar to the established marketing literature [35,36], this paper assumes that the willingness-to-pay $v$ of heterogeneous consumers is uniformly distributed in $[0, 1]$. The market size is normalized to 1. The consumer with willingness-to-pay $v$ gets a net utility $u_2 = v - p_2$ from buying a new product. As consumer does not view remanufactured products as perfect substitutes, the consumer with willingness-to-pay $v$ gets a net utility $u_r = av - p_r$ from buying a new product. $a \in (0, 1)$ denotes the consumer value discount for the remanufactured product [11,13]. If $u_2 > u_r$ and $u_2 > 0$, consumers choose to buy new products in the second period. If $u_r > u_2$ and $u_r > 0$, consumers choose to buy remanufactured products in the second period. In order to ensure that there are remanufactured products sold in the second period, that is $q_r > 0$, we adopt the low-pricing strategy for remanufactured products, that is $p_r < a p_2$ [35,36]. Thus, when $u_2 > u_r$ and $u_2 > 0$, consumers buy new products in the second period and the demand function is $q_2 = 1 - \frac{p_2 - p_r}{1 - a}$, otherwise, $u_r > u_2$ and $u_r > 0$, consumers buy remanufactured products in the second period and the demand function is $q_r = \frac{p_2 - p_r}{1 - a} - \frac{p_r}{a}$. Referring to Yenipazarli [36], the inverse demand functions of new and remanufactured products in the second period are $p_2 = 1 - q_2 - a q_r$ and $p_r = a (1 - q_2 - q_r)$. When the price of remanufactured
products is too high, namely \( p_r \geq \alpha p_2 \), there are only new products in the second period. Thus, we do not emphasize this situation in this paper.

c denotes the unit production cost of the new product. \( c_r = ky^2 \) denotes total recycling and remanufacturing costs of \( y \) units remanufactured products, which means that remanufacturing more used products needs more efforts [36]. \( d \) and \( q_r \) represent the donation quantity and sale quantity of remanufactured products, respectively. Then \( k(q_r + d)^2 \) denotes the total recycling and reprocessing costs to remanufacture \( q_r + d \) units remanufactured products. \( f \) denotes the fixed cost to recycle and reprocess used products. In order to encourage enterprises to implement charitable donations, the government provides a direct subsidy for the manufacturer based on the donation quantity of remanufactured products, which is established in the literature. \( t \) denotes the unit subsidy on the donation of remanufactured products. The donation of remanufactured products can improve the reputation and bring the value addition of the brand. To simplify the calculation, assume that \( b = 0 \). This corresponds to the assumption that the donation of the manufacturer occurs only when the government subsidy is effective.

There are many criteria for environmental impact, such as the use of raw materials, energy consumption, and greenhouse gas emissions. Total carbon emissions is recognized worldwide as a measure of environmental impact [35]. When compared with new product, remanufactured product is considered more environmentally friendly. Thus, we assume that the unit carbon emission of new product is 1, and then the unit carbon emission of remanufactured product is \( \delta \). \( \delta \in (0, 1) \) represents the emissions intensity of remanufactured products. The smaller \( \delta \), the smaller environmental impact of remanufactured products. Moreover, the total carbon emissions depend on the production quantity of new and remanufactured products. Hence, under the strategy without remanufacturing, the environmental impact of OEM is \( E^N = q_1 + q_2 \), and under the strategy with remanufacturing, the environmental impact of OEM is \( E^D = (q_1 + q_2) + \delta(q_r + d) \).

We construct and solve the two-period dynamic programming model in two stages, since the second-period decisions depend on the first-period sales quantity of new products. As is seen in Figure 1, the decision-making sequence is presented as follows: (1) the OEM first determines the first-period production decisions; and, (2) then the OEM determines the second-period production decisions. The mathematical optimization involves just one decision maker, who chooses what to do at each point of time. Thus, the backward introduction is used to solving mathematical optimization of dynamic programming [46]. The solving order is presented as follows: we begin with the second stage where the optimal quantities of the new and remanufactured products are determined, and then solve for the firm’s optimal first-period production decisions.

Relevant symbols are summarized in Table 2.

| Symbols | Description |
|---|---|
| Decision Variables | |
| \( q_1, p_1 \) | Sales quantity and price of new product in period 1 |
| \( q_2, p_2 \) | Sales quantity and price of new product in period 2 |
| \( q_r, p_r \) | Sales quantity and price of remanufactured product in period 2 |
| \( d \) | Donation quantity of remanufactured product in period 2 |
| Parameters | |
| \( \alpha \) | Consumer value discount for the remanufactured product |
| \( \rho \) | Collection rate of used products at the end of period 1 |
| \( c \) | Manufacturing cost of new product |
| \( c_r = ky^2 \) | Total recycling and reprocessing cost to remanufacture \( y \) units |
| \( f \) | Fixed cost for remanufactured products |
| \( t \) | Donation subsidy for remanufactured products |
| \( \delta \) | The emissions intensity of remanufactured products |
4. Model Formulation and Solution

4.1. OEM Profits without Remanufacturing (N)

Under the strategy without remanufacturing, the manufacturer provides new products for customers both in the first and second period. Because the manufacturer does not collect the used products to remanufacture, the decision-making of OEM in the first period and that in the second period is independent. The function of profit maximization in the first period is $\max_{\{q_1\}} \Pi_1^N = (p_1 - c)q_1$, and the optimal quantity and price are $q_1^{N*} = \frac{1-c}{\alpha}$ and $p_1^{N*} = \frac{1+c}{\alpha}$, respectively. The decision-making in the second period is the same as that in the first period, that is, $q_2^{N*} = q_1^{N*}$ and $p_1^{N*} = p_2^{N*}$. Therefore, without remanufacturing, the total profit of the manufacturer in the two periods is $\Pi_t^N = (1-c)^2/2$, and the total carbon emissions in the two periods is $E_t^N = 1 - c$.

4.2. OEM Profits with Remanufacturing (D)

Under the strategy with remanufacturing, new products exist in both first and second period, but remanufactured products exist only in the second period. Differently, besides for resale, remanufactured products can be used for donation with the motivation of government subsidy. As the decision-making of OEM in the second period is dependent on that in the first period, we solve this optimization problem in two stages. According to backward induction, we start with the second period.

**Second-Period Analysis.** The quantities of resale and donation of remanufactured products in the second period are restricted by the quantity of new products in the first period. The function of manufacturer’s profit maximization in the second period is:

$$\max_{q_2, d, \tilde{q}_r} \Pi_2^D(q_2, q_r, d|q_1) = (p_2 - c)q_2 + p_r q_r - k(q_r + d)^2 + td - f$$

s.t. $q_r + d \leq \rho q_1$ (1)

According to the Karush–Kuhn–Tucker (KKT) optimization conditions, we solve the equilibrium of the profit maximization in the second period. Let $\tilde{q} = \frac{1}{\rho} \rho q_1$ denote the threshold amount of EOL products that can be collected at the end of the first period.

**Proposition 1.** The optimal solution of OEM under the strategy D in the second period is summarized in Table 3.

**Table 3.** The Optimal Solution of original equipment manufacturer (OEM) under the Strategy D in the Second Period.

| $\rho q_1 \leq \tilde{q}$ | $q_2^{D*}$ | $q_r^{D*}$ | $d^{D*}$ | $p_2^{D*}$ | $p_r^{D*}$ |
|--------------------------|------------|------------|------------|------------|------------|
| $1-a-c-t$ | $\frac{ac-t}{2(1-a)}$ | $\frac{\rho q_1 - \frac{ac-t}{2(1-a)}}}{\tilde{q}}$ | $\tilde{q}$ | $\frac{\rho q_1 - \frac{ac-t}{2(1-a)}}}{\tilde{q}}$ | $\frac{\rho q_1 - \frac{ac-t}{2(1-a)}}}{\tilde{q}}$ |
| $\rho q_1 > \tilde{q}$ | $\frac{1-a-c-t}{2(1-a)}$ | $\frac{ac-t}{2(1-a)}$ | $\frac{\rho q_1 - \frac{ac-t}{2(1-a)}}}{\tilde{q}}$ | $\tilde{q}$ | $\frac{\rho q_1 - \frac{ac-t}{2(1-a)}}}{\tilde{q}}$ | $\frac{\rho q_1 - \frac{ac-t}{2(1-a)}}}{\tilde{q}}$ |

For proof, see Appendix A.1.

Proposition 1 shows that threshold $\tilde{q}$ is the function of $t$ and $k$, and has nothing to do with $c$ and $\alpha$. As the remanufacturing cost $k$ increases, then the threshold of the collected EOL product $\tilde{q}$ decreases. With the increase in the government subsidy $t$, the threshold also increases. When the supply of EOL products is limited by the threshold $\tilde{q}$, manufacturers prefer to collect all available EOL products $\rho q_1$ to remanufacture. When the supply of used products is not limited by $\tilde{q}$, the manufacturer can collect and remanufacture the threshold amount of used products. Some of the remanufactured products are used for donation and the rest of them are used for resale. To be noteworthy, after introducing upgraded remanufacturing strategy, regardless that the remanufacturing is constrained, the functional expressions of remanufactured products for resale and new products in the second period remain the
same. According to the functional expression of donation quantity, the supply of the collected used products largely influences the quantity of donation of remanufactured products.

**First-Period Analysis.** Based on the optimal decision in the second period of OEM, we can maximize the total two-period profit \( \max_{q_1} \Pi^D (q_1) = (p_1 - c)q_1 + \max_{q_2, q_r, d} \Pi^D_2 (q_2, q_r, d | q_1) \). Let \( t_D = (1 - c)k \) denote the subsidy threshold of government.

**Proposition 2.** The optimal solution of OEM under the strategy D in two periods is summarized in Table 4.

| Case          | \( q_1^{D*} \) | \( \Pi^D* \) | \( E^D* \) |
|---------------|----------------|-------------|-------------|
| \( t_D \geq \frac{1-c+t}{2(kp^2 + \rho)} \) | \( \frac{(1-c+t)^2}{4(kp^2 + \rho)} \) | \( \frac{(1-c+t)^2}{4(kp^2 + \rho)} - \frac{(a-t)(a-2\alpha + t)}{4(1-a)\alpha} - f \) | \( \frac{1-a-c+t}{2(1-a)} + \frac{(\rho+1)(1-c+t)}{2k\rho^2 + 2} \) |
| \( t < t_D \) | \( \frac{1+c}{2} \) | \( \frac{(1-c)^2}{4(1-a)\alpha} + \frac{2}{\alpha} - \frac{(a-t)(a-2\alpha + t)}{4(1-a)\alpha} - f \) | \( \frac{1}{2} \left( \frac{1+c}{2} - c + \frac{2}{\alpha} + 2 \right) \) |

For proof, see Appendix A.2.

Proposition 2 demonstrates that government subsidy has a threshold \( t_D \), which is negatively related to the cost of new products \( c \), positively related to remanufacturing costs \( k \) and the collection rate \( \rho \), and has nothing to do with the customer value discount \( a \). When the donation subsidy is lower than \( t_D \), the decision-making in the first period and that in the second period are totally independent. At the moment, the first-period optimal solution under strategy D is same as that under strategy N. When the donation subsidy is higher than \( t_D \), the manufacturer decreases the price of new products and thus increases the sale of new products in the first period, in order to ensure that enough used products are obtained in the second period.

According to Propositions 1 and 2, with the increase in the government subsidy, the sales quantity of new products decreases, the donation quantity of remanufactured products increases and the quantities of new products in two periods continuously increase.

**Corollary 1.** When both the sale and donation of remanufactured products exist, the effective subsidy is \( t \in \{ t^M, t^U \} \) if \( c \geq c_R \); \( \{ t_D, t^U \} \) if \( 0 < c < c_R \); \( \{ t^U, t_D \} \) if \( 0 < c < c_R \). Here, \( t^M = \frac{a(c+k\rho-c(a-1)(c-1)\rho)}{1+c^2(a-\alpha^2+k)} \) and \( t^U = ac \). For proof, see Appendix A.3.

Corollary 1 shows that the sale and the donation of remanufactured products are closely related to the donation subsidy and the cost of new products. From the perspective of cost, the whole subsidy region is continuous. The higher the cost of new products, the more difficult the donation of remanufactured products is to occur. The rationale is that the higher the cost of new products, the more profits from the sale of remanufactured products, and the more opportunity cost of donation of remanufactured products. Thus, a higher government subsidy is needed to make up for the opportunity costs of donation of remanufactured products. When the cost of new products is relatively low, the manufacturer donates remanufactured products with a relatively low government subsidy incentive. It is noteworthy that, when \( t \leq t^U \), that is, the subsidy is invalid, the manufacturer does not donate remanufactured products. When \( t \geq t^M \), that is, the subsidy is too high, the manufacturer does not sell remanufactured products. This paper focuses on the case where sale and donation of remanufactured products both exist, therefore does not consider these two special conditions.

5. Comparisons of Different Strategies

Introducing upgraded remanufacturing strategy, including resale and donation, has different impacts on production decision, economic profit, and environmental impact of OEM. In this section,
taking the strategy \( N \) as a benchmark, we analyze the changes in production, economic, and environmental benefits of OEM under the strategy \( D \).

5.1. Comparisons of Production Quantity and Price

First, we compare production quantities and prices of new and remanufactured products between the strategy \( D \) and the strategy \( N \). Let \( \Delta = \Delta^D - \Delta^N \) represent the difference of parameter \( \cdot \) under the two different strategies. Here, \( \cdot \) denotes \( q, d \) and \( p \).

**Proposition 3.** After introducing upgraded remanufacturing strategy including resale and donation, the changes in production quantities and prices of two periods are shown in Table 5.

| \( t \) | \( \Delta \cdot \) | \( \Delta q_1 \) | \( \Delta p_1 \) | \( \Delta q_2 \) | \( \Delta p_2 \) | \( \Delta q_r \) | \( \Delta p_r \) | \( \Delta d \) |
|---|---|---|---|---|---|---|---|---|
| \( t > t^M \) | (\( +, \checkmark \)) | (\( -, \checkmark \)) | (\( +, \checkmark \)) | (\( +, \checkmark \)) | (\( +, \checkmark \)) | (\( +, \checkmark \)) | (\( +, \checkmark \)) |
| \( t \geq t_D \) | (\( +, \checkmark \)) | (\( -, \checkmark \)) | (\( +, \checkmark \)) | (\( +, \checkmark \)) | (\( +, \checkmark \)) | (\( +, \checkmark \)) | (\( +, \checkmark \)) |
| \( t < t_D \) | (0, \( \times \)) | (0, \( \times \)) | (0, \( \times \)) | (0, \( \times \)) | (0, \( \times \)) | (0, \( \times \)) | (0, \( \times \)) |

Note: signs \( +, -, \checkmark, \checkmark, \checkmark \) and \( \times \) denote \( \Delta > 0, \Delta < 0, \Delta = 0 \), monotonic increasing, monotonic decreasing and unrelated with respect to \( t \), respectively.

For proof, see Appendix A.4.

According to Proposition 3, when the government subsidy is high enough, that is, when \( t > t^M \) or \( t \geq t_D \), the manufacturer will collect used products to remanufacture as many as possible, although the supply of used products is limited by the collection rate and the first-period quantity of new products. Thus, \( \Delta q_1 > 0 \) and \( \Delta p_1 < 0 \) mean that the manufacturer decreases the price of new products in the first period to increase the demand for them, and, as the subsidy increases, the production of new products in the first period continuously increases and the price decreases correspondingly. When the government subsidy is not large enough, that is \( t < t_D \), the supply of the cores is not be restricted by the threshold \( \tilde{q} \). Thus, \( \Delta q_1 = 0 \) and \( \Delta p_1 = 0 \) demonstrate that the production quantity and price of new products in the first period under two strategies are the same. Regardless of the government subsidy, \( \Delta q_2 < 0 \) means that new products in the second period will be eroded by remanufactured products. Note that the cannibalization effect of remanufactured products gradually becomes weaker with the increase in the government subsidy. The rationale is that the quantity of donation of remanufactured products squeezes that of the sale of remanufactured products. Thereby, the donation of remanufactured products weakens the cannibalization effect on the new products from the sale of remanufactured products. The donation subsidy does not affect the price of new products in the second period. Affected by the subsidy, the donation of remanufactured products increases gradually, whereas the sale of remanufactured products decreases gradually, resulting in a premium effect of the sale of remanufactured products.

According to Propositions 2 and 3, we can find that, when compared with the strategy \( N \), the quantities of new and remanufactured products increase as the subsidy increases under the strategy \( D \). It demonstrates that the donation subsidy can expand the demand for new and remanufactured products, transfer the landfill and incineration of EOL products, and weaken the cannibalization of remanufactured product.

5.2. Comparisons of Economic and Environmental Benefits

We compare economic profit and environmental impact between the strategy \( D \) and the strategy \( N \), respectively. Because the fixed cost of remanufacturing \( f \) is constant, we set \( f = 0 \) to calculate conveniently. Let \( \Delta \Pi^{D-N}(t) = \Pi^D - \Pi^N \) represent the differences of economic profit without the
fixed cost $f$ between the strategy D and the strategy $N$. Let $\Delta E^{D-N}(t) = E^{D*} - E^{N*}$ represent the differences of environmental impact between the strategy D and the strategy $N$.

Proposition 4. When $t \in \left\{ \begin{array}{ll} (t^M, t^U) & c_R \leq c \\ (t^L, t^U) & 0 < c < c_R \end{array} \right.$

(1) $\Delta \Pi^{D-N}(t)$ is a continuous convex function of $t$ and increases in $t \in (t^L, t^U)$ or $t \in (t^M, t^U)$. when $f = 0$, $\Delta \Pi^{D-N} > 0$ always exists in $t \in (t^L, t^U)$ or $t \in (t^M, t^U)$. Therefore, $\exists t \in (t^L, t^U)$ or $t \in (t^M, t^U)$, if $\Delta \Pi^{D-N}(t) > f$, introducing upgraded remanufacturing strategy, including resale and donation leads to better economic profit.

(2) $\Delta E^{D-N}(t)$ is a continuous increasing function of $t$. $\Delta E^{D-N}(t)$ is affected by the cost of new products $c$, the emissions intensity of remanufactured products $\delta$ and customer value discount $\alpha$. The specific changes are shown as in Table 6.

### Table 6. The Changes in Environmental Impact.

| Case | $\delta > \alpha$ | $0 < \alpha < c_R$ | $\alpha < c < c_L$ | $c_R < \alpha < c_L$ | $c_L \leq \alpha < 1$ |
|------|------------------|------------------|------------------|------------------|------------------|
| $t \in (t^L, t^U)$ | $\Delta E^{D-N}(t) > 0$ | $\Delta E^{D-N}(t) > 0$ | $\Delta E^{D-N}(t) > 0$ | $\Delta E^{D-N}(t) > 0$ | $\Delta E^{D-N}(t) > 0$ |

For proof, see Appendix A.5.

Proposition 4 analyzes the changes of economic and environmental benefits after introducing upgraded remanufacturing strategy, including resale and donation.

From an economic point of view, when the additional profit obtained from sale and donation of remanufactured products can make up for the fixed cost $f > 0$, introducing remanufacturing is profitable, otherwise, no remanufacturing is more effective. The economic advantage resulted from the donation of remanufactured products will increase as the subsidy increases. In other words, the government can help the manufacturer to increase the additional profit that was obtained from subsidy and remanufacturing and overcome the high fixed cost.

From the perspective of environment, when customers consider the remanufactured products not environmentally friendly, that is $\delta > \alpha$, regardless of the cost of new products, introducing remanufacturing leads to a worse environmental impact. On the contrary, when customers consider the remanufactured products to be environmentally friendly, that is $\delta < \alpha$, if the cost of new products is relatively low, that is $0 < c < c_R$, the subsidy interval where environmental impact gets improved depends on the emissions intensity of remanufactured products $\delta$. It is not difficult to see that when the environmental impact of remanufactured products is relatively low, namely $0 < \delta < \delta_1$, the subsidy interval where environmental impact gets improved is $t \in (t^L, t_1)$. However, when the environmental impact is relatively high, namely $\delta_1 < \delta < \alpha$, the subsidy interval where environmental impact gets improved is $t \in (t^L, t_2)$. Note that the relationship $t_2 < t_1 < t_0$ demonstrates that the subsidy interval where environmental impact gets improved becomes larger if $\delta$ is smaller. This is because, the more environmentally friendly the remanufactured products, the smaller the environmental impact of remanufactured products, and the larger the increment of remanufactured products that can be adjusted by the government subsidy.

When customers consider the remanufactured products environmentally friendly, that is $\delta < \alpha$, if the cost of new products is relatively high, that is, $c_R \leq c < c_L$, a higher subsidy is needed to motivate the manufacturer to donate the remanufactured products. At this time, if customers consider the
remanufactured products environmentally friendly, introducing upgraded remanufacturing strategy, including resale and donation, brings improved environmental impact in $t \in (t^M, t_1)$.

When the cost of new products is very high, that is $c_p \leq c < 1$, regardless that whether consumers consider the remanufactured products environmentally friendly, introducing upgraded remanufacturing strategy results in the worse environmental impact.

It is noted that the government can realize a win-win situation of OEM where economic and environmental benefits get improved by adjusting the donation subsidy. Relatively, the low-cost and environmentally friendly manufacturer is easier to realize a win-win situation by donation subsidy.

6. Numerical Analysis

This section provides a more intuitive analysis of the changes in the production decision, economic profit, and environmental impact of OEM after introducing upgraded remanufacturing strategy by the numerical examples. The numerical examples verify the above propositions and conclusions and present some new managerial highlights. The main parameters originate from the literature [11,36,47].

6.1. The Manufacturer’s Production Decision under the Case $D$

The parameters are set as follows: $k = 0.01, \alpha = 0.6, c = 0.1, \rho = 0.6$, then the effective interval of donation subsidy is $t \in (0.0024, 0.06)$. The impact of donation subsidy on production decision in two periods is shown in Figure 2. When $t = 0.0024, d = 0$ means that all of the remanufactured products are used for sale instead of donation. When the subsidy is not high enough, that is $t < 0.0054$, the quantity of new products in the first period is not affected by subsidy, but that in the second period slowly increases as the subsidy increases. In addition, the remanufactured products that are used for donation decrease rapidly, whereas the number of remanufactured products that are used for sale decreases, but the total remanufactured products (including sale and donation) increase rapidly. When the subsidy is high enough, that is $t > 0.0054$, then the new products in the first period slowly increase in order to ensure enough used products that can be collected in the second period. As increasing subsidy weakens cannibalization effect, new products in the second-period increase rapidly. At this moment, the remanufactured products that are used for donation increase more quickly, but remanufactured products that are used for sale decrease rapidly until exit the market. Overall, the total remanufactured products (including sale and donation) increase steadily. When $t = 0.06, q_r = 0$ means that there is no sale of remanufactured products and all of them are used for donation. Thus, the cannibalization effect of remanufactured products does not exist. Obviously, introducing upgraded remanufacturing strategy increases the second-period new and remanufactured products. When the subsidy is high enough, the new products in the first period also increase. The above results prove that introducing upgraded remanufacturing strategy can weaken the cannibalization effect of remanufactured products and expand the demand for new and remanufactured products. All of the above results are consistent with Propositions 1,2 and Corollary 1.

![Figure 2. The Impact of Donation Subsidy on Production Decision in Two Periods.](image-url)
6.2. The Effect of Introducing Upgraded Remanufacturing Strategy on Economic and Environmental Benefits

The parameters are set as follows: $k = 0.01$, $a = 0.6$, $\rho = 0.6$. The economic and environmental benefits of manufacturers become complex after introducing upgraded remanufacturing strategy. The economic profit of the manufacturer depends on not only the fixed cost of remanufacturing $f$ but also the government subsidy $t$, as is shown in Figure 3. When the low cost $c = 0.1$ and $f = 0$, introducing upgraded remanufacturing strategy is profitable, regardless of government subsidy. When $f = 0.005$, the effective government subsidy must be higher than 0.0124955, and when $f = 0.007$, it must be higher than 0.0233318. As the fixed cost of remanufacturing increases, less profit can be acquired after introducing upgraded remanufacturing strategy. As the donation subsidy increases, the manufacturer acquires more additional profit from the subsidy that makes up the fixed cost. As the cost of new products increases, that is $c = 0.21$, the cost advantage of remanufacturing is more and more prominent and the manufacturer can acquire more profits, which is less affected by the fixed cost of remanufacturing. All of the above results are consistent with Proposition 4(1).

![Figure 3. The Effect of Introducing Upgraded Remanufacturing Strategy on Economic Profit.](image)

The environmental impact after introducing remanufactured products radically depends on consumer value discount for the remanufactured product, as is shown in Figure 4a. When consumers’ awareness of remanufactured products is less than the emissions intensity of remanufactured products, that is $\alpha = 0.6 < \delta = 0.65$, introducing upgraded remanufacturing strategy cannot bring better environmental impact. When consumers’ awareness of remanufactured products is more than the environmental impact of remanufactured products, the subsidy interval where the environmental impact gets better depends on the emissions intensity of remanufactured products $\delta$ and the cost of new products $c$. When the cost of new products is relatively low, that is $c = 0.1$, if $\delta = 0.2 < \delta_1$, $\Delta E(t) = 0$ has a unique root $t_1 = 0.0143917 > t_D$ in $t \in (t_D, t^{U})$, thereby the environmental impact getting better in $t \in (t^L, t_1)$. If $\delta = 0.4 > \delta_1$, $\Delta E(t) = 0$ has a unique root $t_2 = 0.00352941 < t_D$ in $(t^L, t_D)$, thereby the environmental impact getting better in $t \in (t^L, t_2)$. When the cost of new products is relatively high, that is, $c = 0.21$, $\Delta E(t) = 0$ has a unique root $t_1 = 0.0249249 > t_D$ in $t \in (t^M, t^{U})$, thereby the environmental impact getting better in $t \in (t^L, t_1)$.

The Figure 4b shows the environmental impact after introducing upgraded remanufacturing strategy when the cost of new products is very high. When $c = 0.3$, $\alpha = 0.6 < \delta = 0.65$ means that consumers consider the remanufactured products to be not environmentally friendly and introducing remanufacturing brings worse environmental impact. In addition, $\alpha = 0.6 > \delta = 0.5$ means that consumers consider the remanufactured products environmentally friendly and introducing remanufacturing brings better environmental impact. At this moment, $\Delta E(t) = 0$ has a unique root $t_1 = 0.072292 > t_D$ in $t \in (t^M, t^{U})$, thereby the environmental impact getting better in $t \in (t^M, t_1)$.
When $c = 0.31$, although $\alpha = 0.6 > \delta = 0.5$, $\Delta E^{D-N}(t) > 0$ exists in $t \in (t^M, t^U)$. This means that for the high cost of new products, the environmental impact cannot get improved after introducing remanufacturing. All the above results are consistent with Proposition 4(2).

![Graph](image1.png)

**Figure 4.** The Effect of Introducing Upgraded Remanufacturing Strategy on Environmental Impact: (a) $c < c_R$; (b) $c > c_R$.

As can be seen from the Figures 3 and 4a, when the cost of new products is relatively high, that is, $c = 0.21$, after introducing upgraded remanufacturing strategy, the manufacturer can realize a win-win situation where economic profit and environmental impact get better in $t \in (0.0116455, 0.0249249)$. When the cost of new products and the fixed cost of remanufacturing are relatively low, that is $c = 0.1$ and $f = 0.005$, after introducing upgraded remanufacturing strategy, the manufacturer can realize a win-win situation where economic profit and environmental impact get better in $t \in (0.0124955, 0.0143917)$. When the cost of new products is relatively low and the fixed cost of remanufacturing is relatively high, that is, $c = 0.1$ and $f = 0.007$, there is no subsidy interval where economic profit and environmental impact simultaneously get better after introducing remanufacturing.

7. Conclusions

Remanufacturing has great economic and environmental potential. Currently, resale is the main way of realizing the value of remanufactured products. Although remanufactured product has the same quality and function as new product does, lack of consumer acceptance of remanufactured products prevents OEM from realizing the full potential value by remanufacturing. Although remanufacturing is proved to be profitable, many enterprises still do not choose to remanufacture, mainly because of internal cannibalization. In order to expand the demand for remanufactured products and weaken the internal cannibalization, this paper introduces the donation of remanufactured products with government subsidy and presents upgraded remanufacturing strategy, including resale and donation of remanufactured products. To better understand the effect of upgraded remanufacturing strategy on the production decision, economic and environmental benefits, we construct a two-period production decision model and examine two different strategies: (1) the absence of remanufacturing; and, (2) the presence of remanufacturing. At first, we solve and analyze the optimal solution under two strategies. Then taking the absence of remanufacturing as a benchmark, we explore the effect of introducing upgraded remanufacturing on production decision, economic profit, and environmental impact.

The findings can be summarized as follows: (1) The donation of remanufactured products is influenced by the government subsidy and the cost of new products. The manufacturer needs to consider the opportunity cost of donating remanufactured products when making decisions about the donation. When the cost of new products is relatively high, the remanufactured products can achieve more profits by sale and more subsidies are needed to stimulate the donation of remanufactured products.
products. (2) From the perspective of subsidy incentive, after introducing upgraded remanufacturing strategy, the quantities of new and remanufactured products both increase. The donation of remanufactured products weakens the cannibalization effect of remanufactured products on new products. At some extreme conditions, namely the subsidy is high enough, all of the remanufactured products are used for donation and the cannibalization effect of remanufactured products will disappear. (3) From the perspective of constraint condition, the quantity of donation of remanufactured products is affected by the quantity of used products that can be collected in the second period. When the subsidy is high enough, the supply of used products will be restricted by the collection rate. In order to collect EOL products as many as possible to meet the requirement of the donation, the manufacturer will increase the production of new products in the first period. (4) From the economic point of view, when compared with the benchmark, whether the upgraded remanufacturing strategy is profitable depends on the fixed cost of the remanufacturing. When the fixed cost is relatively high, the government can ease the pressure of OEM from remanufacturing investment by donation subsidy incentive, thereby guiding manufacturer to remanufacture more EOL products. (5) From the environmental point of view, after introducing upgraded remanufacturing, the environmental impact depends on consumer value discount for the remanufactured product. When consumers consider remanufactured products not environmentally friendly, introducing upgraded remanufacturing will make the environment worse. (6) From an economic and environmental win-win point of view, when consumers consider remanufactured products to be environmentally friendly, the government can realize an OEM’s win-win situation where the economic and environmental benefits get improved by adjusting the donation subsidy. Comparatively speaking, low-cost and environmentally friendly manufacturers are easier to achieve the win-win situation through donation subsidy.

With respect to the limitation of this paper, we focus on complete rationality of the manufacturer, which is common in literature [11,35,36]. Some scholars focus on incomplete rationality, which affects manufacturer’s decision. In addition, we consider the government subsidy to be exogenous. In fact, the subsidy is determined by the government. At last, this paper only focuses on the monopoly market structure where there is merely one integrated manufacturer with remanufacturing capability. However, there are also situations where the manufacturer gives up remanufacturing and the third remanufacturer collects EOL products and remanufactures as a competitor.

In future research, empirical research on the donation of remanufactured products needs to be supplemented and perfected. Because the government determines the donation subsidy, the subsidy is endogenous. It is worth studying that how the government determines donation subsidy with the goal of maximizing the social welfare. We can also consider that the reputation brought by donation is private information and incomplete information will result in a more complex analysis.

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Conflicts of Interest: We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work. There is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.
Appendix A

Appendix A.1

Proof of Proposition 1. The decision variables are \( q_n, q_r \) and \( d \cdot \Pi^D \) is concave in \((q_2, q_r, d)\).

Hessian matrix \( H = \begin{pmatrix} -2 & -2a & -ta \\ -2a & -2k - 2a & -2k \\ 0 & -2k & -2k \end{pmatrix} \). It is simple to verify that the Hessian matrix is a negative definite matrix. The Lagrangean and the Karush-Kuhn-Tucker optimality conditions are:

\[
\Pi^D_2 = (1 - q_2 - \alpha q_r - c) q_2 + \alpha (1 - q_2 - q_r) q_r - k (q_r + d)^2 + t d - f + \lambda (\rho q_1 - q_r - d)
\]

\[
\frac{\partial \Pi^D_2}{\partial q_2} = 1 - 2a q_r - 2q_2 - c = 0
\]

\[
\frac{\partial \Pi^D_2}{\partial q_r} = a - 2dk - 2(a + k)q_r - \lambda - 2a q_2 = 0
\]

\[
\frac{\partial \Pi^D_2}{\partial d} = -2k(d + q_r) - \lambda + t = 0
\]

\[
\lambda (\rho q_1 - q_r - d) = 0.
\]

Because the multipliers can be either zero or positive, there are two cases of interest to us.

Case 1. \( \lambda > 0 \)

Solving the optimality conditions give \( q^D_2 \) = \( \frac{1 - a - c + t}{2(1 - a)} \), \( q^D_r \) = \( \frac{\alpha c - t}{2(1 - a) \alpha} \), \( d^D \) = \( \rho q_1 - \frac{\alpha c - t}{2(1 - a) \alpha} \) and \( \lambda = t - 2k \rho q_1 \). The condition \( \lambda > 0 \) gives \( \rho q_1 < \frac{t}{2k} = \tilde{q} \). The prices and economic profit are as follows:

\[
p^D_2 = \frac{c+1}{2}, p^D_r = \frac{\alpha + t}{2}, \Pi^D_2 = \frac{\alpha(c-1)^2}{4(1-a)} + \rho q_1 (t - k \rho q_1) + \frac{(t-a)(a-2ac+t)}{4(1-a)\alpha} - f.
\]

Case 2. \( \lambda = 0 \)

Solving the optimality conditions give \( q^D_2 \) = \( \frac{1 - a - c + t}{2(1 - a)} \), \( q^D_r \) = \( \frac{\alpha c - t}{2(1 - a) \alpha} \), \( d^D \) = \( \tilde{q} - \frac{\alpha c - t}{2(1 - a) \alpha} \) and \( \lambda = 0 \). The condition \( q_r + d < \rho q_1 \) gives \( \rho q_1 > \frac{t}{k} = \tilde{q} \). The prices and economic profit are as follows:

\[
p^D_2 = \frac{c+1}{2}, p^D_r = \frac{\alpha + t}{2}, \Pi^D_2 = \frac{\alpha(c-1)^2}{4(1-a)} + \frac{(t-a)(a-2ac+t)}{4(1-a)\alpha} + \tilde{q}^2 - f.
\]

Proposition 1 is proven.

Appendix A.2

Proof of Proposition 2. It is simple to verify that \( \Pi^{D*}_2(q_1) \) is continuous at \( \rho q_1 = \tilde{q} \). We maximize the total two-period profit \( \Pi^D_2(q_1) \), which is continuously differentiable and strictly concave in \( q_1 \).

Case 1. \( \rho q_1 < \tilde{q} \)

The profit function of OEM in two periods is as follow:

\[
\Pi^D(q_1) = (1 - q_1 - c) q_1 + \frac{(c - 1)^2}{4(1-a)} + \rho q_1 (t - k \rho q_1) + \frac{(t-a)(a-2ac+t)}{4(1-a)\alpha} - f
\]

Solving the first-order condition gives \( \frac{\partial \Pi^D}{\partial q_1} = 1 - c - 2q_1 (k \rho^2 + 1) + \rho t \). Solving the second-order condition gives \( \frac{\partial^2 \Pi^D}{\partial q_1^2} < 0 \). At \( \rho q_1 = \tilde{q} \), \( \frac{\partial \Pi^D}{\partial q_1} = 1 - c - \frac{t}{k \rho} \). If \( t > (1-c)k \rho = t_D \), then \( \frac{\partial \Pi^D}{\partial q_1} < 0 \), and the maximum is reached at \( \rho q^{D*}_1 \) < \( \tilde{q} \). At this moment, \( q^{D*}_1 = \frac{1-c+pt}{2(k \rho^2 + 1)}, \Pi^{D*} = \frac{(1-c+pt)^2}{4(k \rho^2 + 4)} + \frac{(1-c)^2}{4(1-a)\alpha} - \frac{(a-t)(a-2ac+t)}{4(1-a)\alpha} - f \) and \( E^D = \frac{1-a-c+\rho t}{2(1-a)} + \frac{(\rho t + 1)(1-c+\rho t)}{2k \rho^2 + 2} \).
Case 2. \( \rho q_1 \geq \tilde{q} \)

The profit function of OEM in two periods is as follow:

\[
\Pi^D(q_1) = (1-q_1-c) \ast q_1 + \frac{(c-1)^2}{4(1-\alpha)} + \frac{(t-\alpha)(\alpha^2+4)}{4(1-\alpha)^2} + \frac{t^2}{4k} - f
\]

Solving the first-order condition gives \( \frac{\partial \Pi^D}{\partial q_1} = -c - \frac{t}{tk} + 1 \). Solving the second-order condition gives \( \frac{\partial^2 \Pi^D}{\partial q_1^2} < 0 \). At \( \rho q_1 = \tilde{q}, \frac{\partial \Pi^D}{\partial q_1} = -c - \frac{t}{tk} + 1 \). If \( t \leq (1-c)kp = t_D \), then \( \frac{\partial \Pi^D}{\partial q_1} > 0 \), and the maximum is reached at \( \rho q_1^{D_1} = \tilde{q} \). At this moment, \( q_1^{D_1} = \frac{1-c}{2}, \Pi^{D_1} = \frac{(1-c)^2}{4} + \frac{(1-c)^2}{4(1-\alpha)} + \frac{t^2}{4k} - \frac{(\alpha-t)(\alpha^2+4)}{4(1-\alpha)^2} - f \) and \( E^D = \frac{1}{2} \left( \frac{t-c}{t-a} + \frac{4t}{t} + 2 \right) \).

Proposition 2 is proven.

Appendix A.3

Proof of Corollary 1. \( q^{D_1} > 0 \) requires \( t < ac = l^U \). When \( t > (1-c)kp = t_D \), \( d^{D_1} < 0 \) requires \( t > \frac{ack}{a-a^2+k} = l^U \). When \( t > (1-c)kp = t_D \), \( d^{D_1} > 0 \) requires \( t > \frac{\alpha \cdot (c-k^2)}{4(1-\alpha)^2} = l^M \). We can verify that if \( c \geq c_R, t^M \geq t_D \), otherwise, \( t^M < t_D \). Thus, if \( 0 < c < c_R \), the effective subsidy is \( t \in (l_1^U, l^U_1) \), otherwise, the effective subsidy is \( t \in (l^M, t^U_1) \).

Corollary 1 is proven.

Appendix A.4

Proof of Proposition 3. When \( t \geq t_D \) or \( t \geq t^M \), we can obtain \( \Delta q_1 > 0, \Delta p_1 < 0, \Delta q_2 < 0, \Delta p_2 = 0, \Delta q_r > 0, \Delta p_r > 0 \) and \( \Delta d > 0 \). In addition, \( \frac{\partial \Delta q_1}{\partial t} > 0, \frac{\partial \Delta q_2}{\partial t} > 0, \frac{\partial \Delta q_r}{\partial t} > 0, \frac{\partial \Delta d}{\partial t} > 0 \) and \( \frac{\partial \Delta p_2}{\partial t} = 0 \) and \( \frac{\partial \Delta p_1}{\partial t} < 0 \).

When \( t < t_D \), we can obtain \( \Delta q_1 = 0, \Delta p_1 = 0, \Delta q_2 < 0, \Delta p_2 = 0, \Delta q_r > 0, \Delta p_r > 0 \) and \( \Delta d > 0 \).

In addition, \( \frac{\partial \Delta q_1}{\partial t} = 0, \frac{\partial \Delta q_1}{\partial t} = 0, \frac{\partial \Delta q_2}{\partial t} > 0, \frac{\partial \Delta q_2}{\partial t} < 0, \frac{\partial \Delta q_r}{\partial t} > 0 \) and \( \frac{\partial \Delta d}{\partial t} > 0 \).

Proof of Proposition 3 is proven.

Appendix A.5

Proof of Proposition 4. First, we can verify that \( \Delta \Pi^{D-N}(t) \) is continuous at \( t = t_D \). We assume \( f = 0 \).

When \( t \geq t_D \) or \( t \geq t^M \), \( \Delta \Pi^{D-N}(t) = \frac{1-c}{4\rho x^2+t+4} + \frac{(c-1)^2}{4(1-\alpha)} + \frac{(t-\alpha)(\alpha^2+4)}{4(1-\alpha)^2} - \frac{1}{2}(c-1)^2 \).

Let \( \frac{\partial \Delta \Pi^{D-N}(t)}{\partial t} = 0 \), we obtain \( t = t^M \). When \( c \geq c_R, t^M \geq t_D \), otherwise, \( t^M < t_D \). Thus, \( \frac{\partial \Delta \Pi^{D-N}(t)}{\partial t} > 0 \) in \( t \in [t_D, l^U_1] \) or \( t \in [t^M, l^U_1] \). In addition, \( \frac{\partial^2 \Delta \Pi^{D-N}(t)}{\partial t^2} = \frac{1}{2(1-\alpha)^2} + \frac{2\rho x^2+4}{4(1-\alpha)^2} > 0 \). At last, we obtain \( \Delta \Pi^{D-N}(t) > 0 \).

When \( t < t_D \), \( \Delta \Pi^{D-N}(t) = \frac{1-a)(\alpha^2+k(t-a)^2}{4(1-\alpha)^2} > 0, \frac{\partial \Delta \Pi^{D-N}(t)}{\partial t} > 0 \) in \( t \in (l_1^U, l^U_1) \), \( \frac{\partial^2 \Delta \Pi^{D-N}(t)}{\partial t^2} = \frac{x^2-a^2}{4(x^2-a^2)} > 0 \).

Proposition 4(1) is proven.

First, we can verify \( \Delta E^{D-N}(t) \) is continuous at \( t = t_D \), namely \( \Delta E^{D-N} \{ t < t_D \} = \Delta E^{D-N} \{ t > t_D \} \).

When \( l^U_1 < t < t_D \) and \( c < c_R \), we obtain \( \Delta E^{D-N}(t) = \frac{1}{2} \left( \frac{ac-t}{a-\delta} + \frac{\delta t}{\delta} \right) \) and \( \frac{\partial \Delta E^{D-N}(t)}{\partial t} = \frac{1}{2} \left( \frac{x}{x} + \frac{1}{1-\alpha} \right) > 0 \). Because of \( \Delta E^{D-N}(t^L_1) = \frac{ac(t-\delta)}{2(a+x-a^2)} \), if \( \alpha < \delta \), then \( \Delta E^{D-N}(t) > 0 \) in \( t \in (l_1^U, l^U_1) \).

If \( \delta < a \), then \( \Delta E^{D-N}(t^L_1) < 0 \), thus \( \Delta E^{D-N}(t) \) has a unique root \( t_2 \). If \( t_1 < \delta < a \), then \( t_1 < t_2 < t_D \). At the moment, \( \Delta E^{D-N}(t) < 0 \) in \( (l^U_1, t_2) \) and \( \Delta E^{D-N}(t) > 0 \) in \( (t_2, l^U_1) \). When \( 0 < \delta < \delta_1 \), then \( t_2 > t_D \) and \( \Delta E^{D-N}(t) < 0 \) in \( (l_1^U, t^U_1) \).
We obtain \( \Delta E_{D-N}(t) = \frac{a - 2c + \epsilon - 1}{2(1 - \delta)} + \frac{\delta \epsilon + (1 - c + \epsilon) \epsilon}{2k \epsilon + 2} \) and \( \frac{\partial \Delta E_{D-N}(t)}{\partial t} = \frac{\delta \epsilon + (1 - c + \epsilon) \epsilon}{2k \epsilon + 2} > 0 \). When \( \alpha < \delta \), then \( \Delta E_{D-N}(t_D) > 0 \) in \( t \in (t_U, t_L) \). When \( \delta < \delta_1 < \alpha \), then \( \Delta E_{D-N}(t_D) < 0 \). At the moment, \( \Delta E_{D-N}(t) \) has a unique root \( t_1 > t_D \). We obtain \( \Delta E_{D-N}(t) < 0 \) in \( t \in (t_1, t_2) \) and \( \Delta E_{D-N}(t) > 0 \) in \( t \in (t_2, t_U) \).

When \( t < t_U \) and \( c < c_R \), we obtain \( \Delta E_{D-N}(t) = \frac{a - 2c + \epsilon - 1}{2(1 - \delta)} + \frac{\delta \epsilon + (1 - c + \epsilon) \epsilon}{2k \epsilon + 2} \) and \( \frac{\partial \Delta E_{D-N}(t)}{\partial t} = \frac{\delta \epsilon + (1 - c + \epsilon) \epsilon}{2k \epsilon + 2} > 0 \). When \( \delta > \alpha \), then \( \Delta E_{D-N}(t_M) > 0 \). Thus, \( \Delta E_{D-N}(t) > 0 \) in \( t \in (t_M, t_U) \). When \( 0 < \delta < \alpha \), if \( c > c_R \), then \( \Delta E_{D-N}(t_M) > 0 \). Thus, \( \Delta E_{D-N}(t) > 0 \) in \( t \in (t_M, t_U) \). If \( c_R < c < c_R \), then \( \Delta E_{D-N}(t_M) < 0 \), thus \( \Delta E_{D-N}(t) \) has a unique root \( t_1 > t_D \). We obtain \( \Delta E_{D-N}(t) < 0 \) in \( t \in (t_M, t_1) \) and \( \Delta E_{D-N}(t) > 0 \) in \( t \in (t_1, t_U) \).

Proposition 4(2) is proven.

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