Is Remanufacturing Subsidy Effective All the Time? Investigation of Market Segmentation with Replacement Consumers

Miao-Miao Wang, Jun Wu, Xin-Yu Chen, Tao Tian, Xiao-Xi Zhu*

Abstract—**This research is inspired by a government program intended to promote remanufacturing consumption through trade-ins. Be different from former subsidy programs which are provided for remanufacturing consumption, this program is provided solely for buy remanufactured products through trade-ins. To investigate the effect of government subsidy, we established profit maximizing models by considering primary and replacement consumers' segmented purchasing behaviors for the new and remanufactured products. Analysis shows that the government subsidy program will do damage to the consumption of remanufactured products on the primary market although it has been proved to be effective in promoting remanufacturing consumption on the replacement segment. Results show that whether the manufacturer's profit is positively influenced by the fiscal program depends on the production cost of remanufactured products, and the manufacturer's profit will always increase with government subsidy when the remanufacturing cost is low enough. In addition, when the price of the remanufactured product is not high, the market size of primary consumers plays a positive role in promoting the consumption of remanufactured products through trade-ins. Results also suggest that, to make more profit on the selling side, the manufacturer does not always benefit directly from collecting the used product. We also investigate how the manufacturer makes his strategic selection on pricing strategy with key parameters.**

Index Terms—**Closed-loop supply chain; Government subsidy; Trade-ins; Pricing strategy; Remanufacturing**

I. Introduction

Remanufacturing has many advantages and has been proposed by a number of scholars [1-4]. The key reasons that a firm chooses to collect used product can be summarized as two points. The first one is environmental law regulated and promulgated by the government. In 2003, the European Union announced Waste Electrical and Electronic Equipment (WEEE) directive to regulate and force relevant firms to collect the used products. Government laws act as an external force in inducing firms to adopt remanufacturing [5-6]. The second reason which can be explained as an endogenous factor is that remanufacturing can be utilized as a profitable tool. Generally speaking, the production cost of a remanufactured product is considered to be lower than that of a new product [7-9]. However, there has always been the fact that the consumer awareness of remanufactured products is still low, which corresponds to the fact that the market scale of remanufactured products is too low [10-12].

Government intervention plays an important role in the operations of the reverse logistics field [13-15]. In recent years, the Chinese government has announced a special subsidy program to promote consumers who own used product to buy remanufactured product through trade-ins [16]. The policy is aimed at promoting the sales volume and amplifying the market share of remanufactured products (products such as motor engine and gear box, see Figure1). Different from previous subsidy programs that are restricted to benefit the holding consumers who tend to buy new products through trade-ins, the current subsidy program is focusing on benefiting holding consumers who are intending to buy remanufactured products. The environmental objective of this policy is to recycle used product from holding consumers.

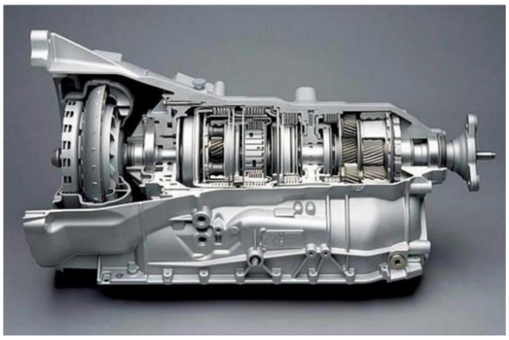

Figure 1: Gear box-one of the subsidy objects of the government program

As an effective mode for resource recovery, remanufacturing has been widely recognized in practice. However, the unstable supply of used products highlight the importance of production planning in remanufacturing. Remanufacturing needs a continuous supply of raw materials from obsolete/used products. Therefore, to ensure the

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Miao-Miao Wang is an associate professor of the College of Economics & Management, Anhui Agricultural University, Hefei, 230036, P.R. China (e-mail: wangmiaomiao@ ahau.edu.cn).

Jun Wu is a postgraduate student of the College of Economics & Management, Anhui Agricultural University, Hefei, 230036, P.R. China (e-mail: 1250379329@qq.com).

Xin-Yu Chen is a postgraduate student of the College Economics & Management, Anhui Agricultural University, Hefei, 230036, P.R. China (e-mail: 1834566419@qq.com).

Tao Tian is a professor of the College of Economics & Management, Agricultural University, Hefei, 230036, P.R. China (e-mail: tiantao@ahau.edu.cn).

Xiao-Xi Zhu is an associate professor of the School of Management, Hefei University of Technology, Hefei, 230009, P.R. China (corresponding author; phone: 86-0551-62901485; fax: 86-0551-62901485; e-mail: zhuxiaoxi@hfut.edu.cn).

sufficiency of cores required for remanufacturing, the problem of pricing used products becomes an important issue [17-18]. As a special business model, trade-ins play important roles in both forward supply chain (for selling new/remanufactured products) and reverse supply chain (for collecting used products). In 2009, the Chinese government issued a subsidy project which only subsidizes those consumers who buy new goods (including televisions, refrigerators, air conditioners and washing machines) through trade-ins. The project has received great social attention and significant business achievement. In recent years, selling prouct through trade-in has been widely spread in various industries such as automobiles and household appliances. The implementation of trade-ins can not only improve consumers' awareness of environmental protection, but also cultivate brand loyalty[19]. In addition, recycling also plays an important role in promoting the environmental performance of closed loop supply chain (CLSC) [20,21].

The program we investigated is significantly different from previous government stimulus plans: first, compared with previous remanufacturing subsidies, the current policy only subsidizes replacement consumers. It is also different from the previous trade in subsidy: the beneficiaries of the former trade in subsidy are the replacement consumers who purchase new products, while the current policy is to subsidize the replacement consumers who buy remanufactured products. In such a context, this paper seeks to provide a better understanding on the following questions:

(1) What are the impacts of the segmented subsidy program on the cannibalization between new and remanufactured products? Since the objective of the government is to promote remanufacturing consumption, then under what condition will it be effective?

(2) How does the vary of market potential affect the effectiveness of the program? Will the government -subsidized remanufacturing activity always beneficial to the firm's profits?

We organize the rest of this paper as follows. Section II analyzed the related literature. Section III describes the research problem and develops the mathematical models. Section IV derives the equilibrium results and studies impacts on demands. Through analytical studies, Section V investigates the impacts of the trade old for remanufactured subsidy on profits. Finally, conclusions are summarized in Section VI.

II. RELATED LITERATURE

Since this paper focuses on the effectiveness of government promotion plan on CLSC with trade-ins, this section gives the related literature from two parts: Government regulation and subsidy on CLSC, trade-ins in reverse logistics.

A. Government regulation and subsidy on CLSC

Recycling and remanufacturing can save resources and protect the environment, which has become the focus of government and enterprises. The government public policy can regulate the market to a certain extent, and many scholars have studied the impact of government regulation and subsidy on CLSC. Dou and Cao [22] jointly measured the performance of environment and economy of three CLSC under carbon tax regulation. De and Giri [23] studied a CLSC, emphasizing management, scheduling and path planning to achieve economic development without damaging the environment. They also examined CLSC to save transportation costs, including carbon emissions from heterogeneous fleets with restricted capacity. Taleizadeh et al. [24] exhibited the impact of collection-remanufacturing process on carbon emission reduction, product quality enhancement and supply chain performance improvement. Dibat and Jebali [25] addressed the programming issue of durable consumer goods closed-loop supply chain network in the context of recycling regulations. Yang and Xu [26] found that under carbon emission permits, subsidies can encourage manufacturers to invest more money in low-carbon technologies to reduce total carbon emissions, thus increasing the profits of manufacturers and the whole CLSC. Taking the government subsidy on new energy vehicle market as the research background, Zhao et al. [27] constructed a profit distribution model for closed-loop supply chain members with or without government subsidies and when the targets of government subsidies are different. They studied how the profits of supply chain members are distributed, and analyzed the impact of different types of government subsidies on the performance improvement of the whole closed-loop supply chain system. Considering the low-carbon characteristics of manufactured goods, He et al. [28] explored a dual channel CLSC in which manufacturers can sell new products through retailers and sell remanufactured products through e-commerce platforms with government subsidies. Wang et al. [29] discussed the effect of government subsidies and supply chain leader's altruistic preferences on the operation of low-carbon e-commerce CLSC. Zhang et al. [30] investigated the production pattern and pricing strategy of double cycle closed-loop supply chain considering equity concerns. Zhang et al. [31] studied the production pattern and pricing of closed-loop supply chain based on consumers’ preference.

B. Trade-ins in reverse logistics

The implementation of trade-ins can improve consumers' awareness of environmental protection, and is conducive to the cultivation of brand loyalty. Many scholars have made a series of researches on the issue of trade-ins from different perspectives. Li and Xu [32] compared the trade-in and leasing of products with innovation, explored the best pricing tactics for leasing and trade-in, studied their effects on the manufacturer's profit, and compared the performance of the two modes. Xu et al. [33] studied the impacts of trade-in and price discount on the likelihood of alternative purchase. They found that the effectiveness of the promotion methods is determined by the level to which new products can replace old products. Cao et al. [34] investigated the best trade-in strategy of B2C platform with dual format retail model. But they didn't take consumer costs into account. Hu et al. [35] established a game theory analysis model by analyzing the buying behavior of short-term consumers and long-term consumers to determine the optimal price and best trade-in discount for next-generation products. In order to determine the best channel model for the old-for-new, Xiao et al. [36] constructed a traditional retail channel model and a dual channel model under two cases: with trade-in and without trade-in. Cao et al. [37] considered an enterprise that sells new products to new consumers and sells products to substitute consumers through trade-in services to explore the best decisions in the case of cash and gift cards, and determined the best way to payment of price discounts. Sheu and Choi [38] discussed the value-oriented pricing strategy of the trade in upgrade project by employing a multi-method approach to thoroughly investigate the behavioral pricing and market competition challenges related to trade-in. Kuik et al. [39] explored the optimal product configuration decision problem for product returns towards sustainable manufacturing. Kuik et al. [40] analyzed the product redesign decision for remanufactured products in recyclable manufacturing system.

Most of the studies on government subsidies in the above literature focus on the subsidies of new products in the process of trade in to promote the sales of new products, the policy proposed in this paper only subsidizes replacement consumers who buy remanufactured products, and this paper attempt to illustrate the effectiveness of using trade-in on selling remanufactured products.

III. Main assumptions and model framework

To achieve cost saving and to be eco-friendly, many firms resort to the remanufacturing option. However, motivated by either regulations or profits, the remanufacturing firm will inevitably be disturbed by the differentiation between new and remanufactured products. We consider a monopolist providing new and remanufactured products for the market to maximize its net profit. The monopoly firms would worry about the cannibalization problem existing between the two differentiated products. The purchasing intention of consumers with different types have been addressed by several researchers [41-43]. In our study, the potential consumers can be classified into the following two market segments:

(1) Primary first-time buyers;

(2) Potential replacement consumers. One can choose to keep the used product or to trade-in with the seller (manufacturer) for new and remanufactured product.

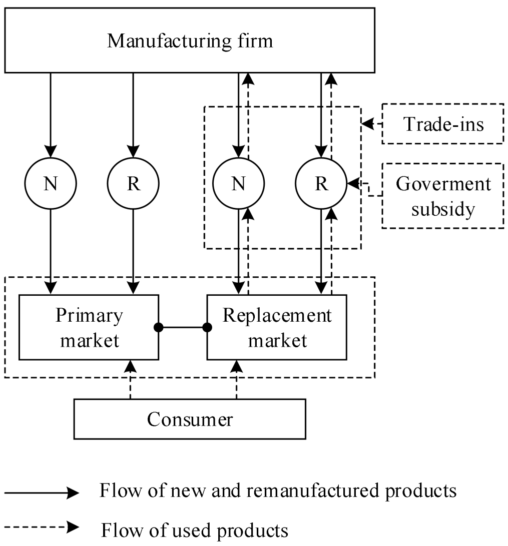

Figure 2. Market structure of the model

Different from the first-time buyers, the holding consumers should dispose their old products when they buy new (or remanufactured) ones. Thus, providing government subsidy would intuitively help in promoting their potential purchases (see Figure 2). The consumers who are on their first purchase will make their purchase decisions merely according to the utilities obtained from the product they choose. Thus, the proportions of these two kinds of consumers play an important role when analyzing the pricing decision of the manufacturer. The decision problem of the (re)manufacturer is formulated within a single-period planning horizon. The remanufactured product has different quality than the new product. The consumers are heterogeneous and their valuations are in a uniform distribution form. For ease of modelling, all the used products are assumed to be with identical quality.

The demand functions are derived according to the segmented consumers' purchase and return behaviors, which are expected to analytically describe market sales in an accurate manner. The related parameters used in the paper and the decision variables of the manufacturer are listed in Table I.

TABLE I
NOTATIONS.

Parameter	Definition
c_n	Unit production cost of a new product.
c_r	Unit production cost of a remanufactured product. Here c_r is assumed to be lower than c_n.
ψ	The salvage value index of the used product. For simplicity, we consider the obsolete products to be identical.
θ	Consumers are heterogeneous with respect to their WTP (willingness-to-pay) θ, which is uniformly distributed in [0, 1].
γ	The quality retention index, which satisfies $0<\gamma<1$. Given the quality retention index rate, the holding product is valued as $(1-\gamma)\theta$ for the potential replacement consumers.
ϕ	Unit government subsidy provided for the replacement for a remanufactured product. In order to avoid infinite production, it is required that $\phi \le c_n$ and $\psi \le c_n$.
ρ	Consumer's utility depreciation for a remanufactured product compared to a new product. Here we assume $\rho > 1-\gamma$. This assumption is reasonable as a remanufactured product is generally considered to be functionally better than a used product.
Δ	If the market size of potential replacement market is τ, then it is feasible to assume that the market size of the primary consumer is $\Delta\tau$. $\Delta \ge 1$ means market expansion, and $\Delta < 1$ implies market shrinkage.
$\tilde{q}_{2n}/q_{2n}$	Demand for the new product respectively from new and replacement segments.
$\tilde{q}_{2r}/q_{2r}$	Demand for the remanufactured product respectively from new and replacement segments.
p_{2n}/p_{2r}	Price charged by the manufacturer for a new product and for a remanufactured product p_{2r} is assumed to be lower than p_{2n}.
p_{2t}	Unit trade-in rebate provided by the seller. The actual price paid for a remanufactured product is $(p_{2r}-p_{2t})$. Here we assume the seller provides an identical rebate for both new and remanufactured product.

A. Consumers' choice in primary segment

There are two consumer segments lie on the market, primary and replacement market (see Figure 3). A primary consumer who buys a new product will obtain a total utility of $\tilde{U}_{2n} = \theta - p_{2n}$, and a primary consumer who buys a remanufactured product will obtain a total utility of $\tilde{U}_{2r} = \rho\theta - p_{2r}$. When $\tilde{\theta} = (p_{2n} - p_{2r})/(1-\rho)$, a primary consumer is indifferent to the two products. Thus, a primary consumer finally chooses a new product if and only if $\tilde{U}_{2n} \geq 0$ and $\tilde{U}_{2n} \geq \tilde{U}_{2r}$, and chooses a remanufactured product when $\tilde{U}_{2r} \geq 0$ and $\tilde{U}_{2r} \geq \tilde{U}_{2n}$ is satisfied.

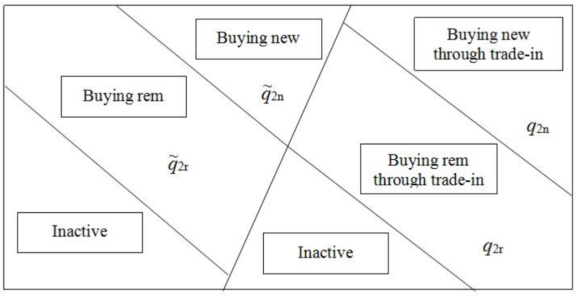

Figure 3. Market segmentation of two products on two separated markets

B. Consumers' choice in replacement segment

The replacement consumer's total utility who buys the new product is $U_{2n} = \theta - p_{2n} + p_{2t} - \theta(1-\gamma)$, and the replacement consumer's total utility who buys the remanufactured product through trade-in is $U_{2r} = \rho\theta - p_{2r} + p_{2t} - \theta(1-\gamma) + \phi$. When $\theta = (p_{2n} - p_{2r} + \phi)/(1-\rho)$, a replacement consumer is indifferent to the two products. Thus, a replacement consumer finally chooses a new product if and only if $U_{2n} \geq 0$ and $U_{2n} \geq U_{2r}$, and chooses to trade-in a remanufactured product if and only if $U_{2r} \geq 0$ and $U_{2r} \geq U_{2n}$. To give the complete form of the profit functions, we need to formulate the demands according to the consumers' self-selection.

C. Demand characterization

On the primary market, we have the following statements:

(1) Case ***L***. When the price of the remanufactured product is not that high, i.e., $p_{2r} \leq \rho p_{2n}$ and $p_{2n} \leq p_{2r} + 1 - \rho$, which can be simplified into $p_{2r}/\rho \leq p_{2n} \leq p_{2r} + 1 - \rho$, the primary consumers will have the following demands for the new and remanufactured products:

$$\tilde{q}_{2n} = \Delta\tau\left(1 - \frac{p_{2n} - p_{2r}}{1-\rho}\right) \text{ and}$$

$$\tilde{q}_{2r} = \Delta\tau\left(\frac{p_{2n} - p_{2r}}{1-\rho} - \frac{p_{2r}}{\rho}\right) = \Delta\tau\left(\frac{\rho p_{2n} - p_{2r}}{(1-\rho)\rho}\right);$$

(2) Case ***M***. When the remanufactured product's selling price is high enough, specifically $p_{2r} > \rho p_{2n}$, and primary consumers will not buy any remanufactured products. The demands are expressed as:

$$\tilde{q}_{2n} = \Delta\tau(1 - p_{2n}) \text{ and } \tilde{q}_{2r} = 0;$$

(3) Case ***H***. When the new products' selling price is high enough, specifically, i.e., $p_{2r} \leq \rho p_{2n}$ and $p_{2n} > p_{2r} + 1 - \rho$ (as $0 < \rho < 1$, this condition can be simplified as $p_{2n} \geq \max\{p_{2r}/\rho, p_{2r} + 1 - \rho\} = p_{2r}/\rho$), the demands are determined as follows:

$$\tilde{q}_{2n} = 0 \text{ and } \tilde{q}_{2r} = \frac{\Delta\tau(\rho - p_{2r})}{\rho}.$$

For the replacement segment, we have the subsequent models.

(1) Case ***l***. When the remanufactured product's price is not that high, i.e., $p_{2r} \leq [(\rho - 1 + \gamma)p_{2n} + \gamma\phi + p_{2t}(1-\rho)]/\gamma$ and $p_{2n} - p_{2r} + \phi < 1 - \rho$, which can be simplified into $[\gamma(-\phi + p_{2r}) + p_{2t}(\rho - 1)]/(\rho - 1 + \gamma) \leq p_{2n} \leq p_{2r} + 1 - \rho - \phi$, the replacement consumers will trade-in their holding products for the new and remanufactured products. The demands are expressed as:

$$q_{2n} = \tau\left(1 - \frac{p_{2n} - p_{2r} + \phi}{1-\rho}\right)$$

$$q_{2r} = \tau\left(\frac{p_{2n} - p_{2r} + \phi}{1-\rho} - \frac{p_{2r} - p_{2t} - \phi}{\rho - 1 + \gamma}\right)$$

(2) Case ***m***. When the remanufactured product's selling price is high, i.e., $p_{2r} > [(\rho - 1 + \gamma)p_{2n} + \gamma\phi + p_{2t}(1-\rho)]/\gamma$, replacement consumers will not buy any remanufactured products. The demands are expressed as:

$$q_{2n} = \tau\left(1 - \frac{p_{2n} - p_{2t}}{\gamma}\right) \text{ and } q_{2r} = 0$$

(3) Case ***h***. When new product's selling price is relatively high, i.e., $p_{2n} \geq [\gamma(-\phi + p_{2r}) + p_{2t}(\rho - 1)]/(\rho - 1 + \gamma)$ and $p_{2n} > p_{2r} + 1 - \rho - \phi$, the demands are determined as follows:

$$q_{2n} = 0 \text{ and } q_{2r} = \tau\left(1 - \frac{p_{2r} - p_{2t} - \phi}{\rho - 1 + \gamma}\right)$$

The existence of parameter τ does not change the results of optimal equilibriums, thus we choose to assume $\tau = 1$ in the following studies. On the two market segments, we totally have 3×3=9 potential scenarios to consider. Because our aim is to investigate the efficiency of government subsidy which is imposed on the replacement activity for remanufactured product only, we choose to neglect to study cases ***m*** and ***M*** ($q_{2r} = 0$) in the following work. Thus, there remain four mix-models to consider. The possible demand functions are listed in Table II.

To achieve analytical findings, we need to make several preliminary assumptions illustrated in Section 3.

IV. ANALYSIS

A. Optimal pricing and production decisions

The decision problem of the manufacturer on the primary market is expressed as:

$$\max \Pi_{\textit{primary market}}(p_{2n}, p_{2r}) = \underbrace{(p_{2n} - c_n)\tilde{q}_{2n}}_{\textit{New product sale}} + \underbrace{(p_{2r} - c_r)\tilde{q}_{2r}}_{\textit{Rem product sale}} \quad (1)$$

The decision problem of the manufacturer on the replacement market can expressed as:

TABLE II
DEMAND FUNCTIONS ON THE TWO MARKET SEGMENTS.

Scenarios	$\frac{p_{2r}}{\rho} \le p_{2n} \le p_{2r} + 1 - \rho$ (Case L)	$p_{2r} \le \rho p_{2n}$ (Case H)
$\frac{\gamma(-\phi + p_{2r}) + p_{2t}(\rho-1)}{\rho - 1 + \gamma} \le p_{2n} \le p_{2r} + 1 - \rho - \phi$ (Case $\boldsymbol{l}$)	$q_{2n} = 1 - \frac{p_{2n} - p_{2r} + \phi}{1-\rho}$ $q_{2r} = \frac{p_{2n} - p_{2r} + \phi}{1-\rho} - \frac{p_{2r} - p_{2t} - \phi}{\rho - 1 + \gamma}$ $\tilde{q}_{2n} = \Delta\left(1 - \frac{p_{2n} - p_{2r}}{1-\rho}\right)$ $\tilde{q}_{2r} = \Delta\left(\frac{\rho p_{2n} - p_{2r}}{(1-\rho)\rho}\right)$	$q_{2n} = 1 - \frac{p_{2n} - p_{2r} + \phi}{1-\rho}$ $q_{2r} = \frac{p_{2n} - p_{2r} + \phi}{1-\rho} - \frac{p_{2r} - p_{2t} - \phi}{\rho - 1 + \gamma}$ $\tilde{q}_{2n} = 0$ $\tilde{q}_{2r} = \Delta\left(1 - \frac{p_{2r}}{\rho}\right)$
$p_{2n} \ge \max\left\{ p_{2r} + 1 - \rho - \phi, \frac{\gamma(-\phi + p_{2r}) + p_{2t}(\rho-1)}{\rho - 1 + \gamma} \right\}$ (Case $\boldsymbol{h}$)	$q_{2n} = 0$ $q_{2r} = 1 - \frac{p_{2r} - p_{2t} - \phi}{\rho - 1 + \gamma}$ $\tilde{q}_{2n} = \Delta\left(1 - \frac{p_{2n} - p_{2r}}{1-\rho}\right)$ $\tilde{q}_{2r} = \Delta\left(\frac{\rho p_{2n} - p_{2r}}{(1-\rho)\rho}\right)$	$q_{2n} = 0$ $q_{2r} = 1 - \frac{p_{2r} - p_{2t} - \phi}{\rho - 1 + \gamma}$ $\tilde{q}_{2n} = 0$ $\tilde{q}_{2r} = \Delta\left(1 - \frac{p_{2r}}{\rho}\right)$

$$\max \Pi_{\text{Replacement market}}(p_{2n}, p_{2r}, p_{2t}) = \underbrace{(p_{2n} - c_n + \psi - p_{2t}) q_{2n}}_{\text{New product sale}} + \underbrace{(p_{2r} + \psi - c_r - p_{2t}) q_{2r}}_{\text{Rem product sale}} \tag{2}$$

The manufacturer tries to maximize the total profits on the two markets, i.e.,

$$\max \Pi^{L\text{-}l} = \Pi_{\text{Primary market}}(p_{2n}, p_{2r}) + \Pi_{\text{Replacement market}}(p_{2n}, p_{2r}, p_{2t}) \tag{3}$$

We start from scenario ***L-l*** in which two differentiated products are covered by both primary and replacement segments. The firm's decision problem is presented as follows

$$\max \Pi^{L\text{-}l}(p_{2n}, p_{2r}, p_{2t}) = (p_{2n} - c_n + \psi - p_{2t}) q_{2n} + (p_{2r} + \psi - c_r - p_{2t}) q_{2r} + (p_{2n} - c_n)\tilde{q}_{2n} + (p_{2r} - c_r)\tilde{q}_{2r} \tag{4}$$

Solving the profit function above we obtain the following findings presented in Proposition 1 as follows.

Proposition 1.

When $c_{r-1} < c_r < \min\{c_{r-2}, c_{r-3}\}$ *is satisfied, the manufacturer is tend to provide two products on two separated segments, and the optimal pricing strategies can be described as follows:*

$$p_{2n} = \frac{1 - \phi + \Delta + \Delta c_n + c_n}{2(1+\Delta)},\quad p_{2r} = \frac{\rho + c_r}{2} \text{ and}$$

$$p_{2t} = \frac{1 - \phi - \gamma + \psi}{2}$$

where, $c_{r-1} = \frac{\rho + \phi - 1 + \Delta(\rho + 2\phi - 1) + (1+\Delta) c_n}{1+\Delta}$, $c_{r-2} = \frac{\rho(c_n + \Delta c_n - \phi)}{1+\Delta}$, *and*

$$c_{r-3} = \frac{\gamma(\phi + 2\Delta\phi) + (\rho - 1)(\Delta\phi - \psi - \Delta\psi) + (1+\Delta)(\gamma + \rho - 1) c_n}{\gamma(1+\Delta)}$$

In Proposition 1, we show that the range of unit remanufacturing cost defines the firm's production and pricing strategies. We provide the optimums of the other three scenarios in Appendix A in Table A1. It can be found that from the expressions of the optimal prices we have $\partial p_{2n}/\partial c_n > 0$ and $\partial p_{2r}/\partial c_r > 0$, which implies that production costs always have a negative effect on the pricing strategy. Besides $\partial p_{2n}/\partial \phi < 0$ and $\partial p_{2r}/\partial \phi = 0$ suggests that government subsidy has a positive effect on pricing new and has no effect on pricing remanufactured products.

The actual buying price of the consumers on the replacement market (actual trade-in price) increase with ϕ as $\partial(p_{2n} - p_{2t})/\partial \phi > 0$ and $\partial(p_{2r} - p_{2t})/\partial \phi > 0$. This finding is interesting because the government's initial incentive is to stimulate the consumption of remanufactured products. However, with the negative effect of ϕ on selling new and remanufactured product for the trade-in consumers, the subsidy policy will be effective. This phenomenon will be explained in proposition 3, and we will further investigate how unit subsidy affects the sales quantities and manufacturer's profit.

B. The effect of subsidy program on remanufacturing consumption

In this sub-section, we will investigate the impact on the demand side of the special subsidy program which is merely imposed on the replacement segment. Before that, we have to give the closed form of the realized demand quantities.

Lemma 1.

The demands for remanufactured products are summarized in Table III.

With these expressions, we found that when the prices of the products are high, which tells that the consumption of the remanufactured products has nothing to do with. The optimal new product production decisions are given in Table III. We will next focus on how government subsidy directly affects the consumption of remanufactured products.

Proposition 2.

(1) $\frac{\partial q_{2r}^{L-l}}{\partial \phi} > 0$, $\frac{\partial q_{2r}^{H-l}}{\partial \phi} > 0$, $\frac{\partial q_{2r}^{L-h}}{\partial \phi} > 0$, *and* $\frac{\partial q_{2r}^{H-h}}{\partial \phi} > 0$;

TABLE III
THE CONSUMPTION QUANTITIES OF REMANUFACTURED PRODUCTS ON TWO SEPARATED MARKETS.

Scenarios	Case L	Case H
Case l	$\tilde{q}_{2r}^{L-l}=\frac{\Delta\left(-\rho\phi+\Delta\rho c_n+c_n\rho-c_r-\Delta c_r\right)}{(1+\Delta)\rho(1-\rho)}$	$\tilde{q}_{2r}^{H-l}=\frac{\Delta(2-\rho-c_r)}{2\rho}$
	$q_{2r}^{L-l}=\frac{\gamma\phi(1+2\Delta)+(\rho-1)\left(\Delta(\phi-\psi)-\psi\right)+\left(\gamma(1-\Delta)+\Delta(\rho-1)+\psi-1\right)c_n-\gamma(1+\Delta)c_r}{2(1+\Delta)(\rho-1+\gamma)(1-\rho)}$	$q_{2r}^{H-l}=\frac{\gamma c_r-\gamma\phi-c_n\rho-c_n\gamma+\psi\rho-\psi+c_n}{2(\rho-1+\gamma)(-1+\rho)}$
Case h	$\tilde{q}_{2r}^{L-h}=\frac{\Delta c_n}{2(1-\rho)}$	$\tilde{q}_{2r}^{H-h}=\frac{\Delta(2-\rho-c_r)}{\rho}$
	$q_{2r}^{L-h}=\frac{\rho+\psi-1-c_r+\gamma+\phi}{2(\rho-1+\gamma)}$	$q_{2r}^{H-h}=\frac{\rho-1+\gamma-c_r+\psi+\phi}{2(\rho-1+\gamma)}$

(2) $\frac{\partial\tilde{q}_{2r}^{L-l}}{\partial\phi}<0$, $\frac{\partial\tilde{q}_{2r}^{H-l}}{\partial\phi}<0$, $\frac{\partial\tilde{q}_{2r}^{L-h}}{\partial\phi}=0$, *and* $\frac{\partial\tilde{q}_{2r}^{H-h}}{\partial\phi}=0$.

For the total remanufacturing consumption, we have

(3) $\frac{\partial\left(\tilde{q}_{2r}^{L-l}+q_{2r}^{L-l}\right)}{\partial\phi}=\frac{\partial\left(\tilde{q}_{2r}^{H-l}+q_{2r}^{H-l}\right)}{\partial\phi}>\frac{\partial\left(\tilde{q}_{2r}^{L-h}+q_{2r}^{L-h}\right)}{\partial\phi}=\frac{\partial\left(\tilde{q}_{2r}^{H-h}+q_{2r}^{H-h}\right)}{\partial\phi}>0$

This finding is important as it shows that the government subsidy program will do damage to the consumption of remanufactured product on the primary market although it has been proved to produce positive effect on promoting remanufacturing consumption on replacement segment. By observing the selling price of the new product $p_{2n}=\left(1-\phi+\Delta+\Delta c_n+c_n\right)/\left[2(1+\Delta)\right]$, we find that p_{2n} decreases with ϕ, i.e., $\partial p_{2n}/\partial\phi=-1/\left[2(1+\Delta)\right]<0$.

However, the selling price of a remanufactured product $p_{2r}=\left(\rho+c_r\right)/2$ has nothing to do with ϕ. The new product exhibits higher quality but has a deceasing price, and thus, the competitive advantage of a new product increases when ϕ increases, and the demand for the remanufactured products shrinks with increasing ϕ.

Lemma 2.

The demands for the new products are summarized in Table IV as below.

TABLE IV
THE CONSUMPTION QUANTITIES OF NEW PRODUCTS ON TWO SEPARATED MARKETS.

Scenarios	Case *L*	Case *H*
Case *l*	$q_{2n}=\frac{(c_n-c_r+\rho-1)(1+\Delta)+(1+2\Delta)\phi}{2(1+\Delta)(-1+\rho)}$	$q_{2n}=\frac{(c_n-c_r+\rho-1+\phi)}{2(-1+\rho)}$
	$\tilde{q}_{2n}=\Delta\left(\frac{(1+\Delta)(1-\rho-c_n+c_r)+\phi}{2(1+\Delta)(1-\rho)}\right)$	$\tilde{q}_{2n}=0$
Case *h*	$q_{2n}=0$	$q_{2n}=0$
	$\tilde{q}_{2n}=\Delta\left(\frac{(1-\rho-c_n+c_r)}{2(1-\rho)}\right)$	$\tilde{q}_{2n}=0$

With the closed forms of demands given above, the following Proposition 3 describes the effect of the subsidy program on the new products sale quantities.

Proposition 3.

(1) $\frac{\partial q_{2n}^{L-l}}{\partial\phi}<0$, $\frac{\partial q_{2n}^{H-l}}{\partial\phi}<0$, $\frac{\partial q_{2n}^{L-h}}{\partial\phi}=0$, *and* $\frac{\partial q_{2n}^{H-h}}{\partial\phi}=0$;

(2) $\frac{\partial\tilde{q}_{2n}^{L-l}}{\partial\phi}>0$, $\frac{\partial\tilde{q}_{2n}^{H-l}}{\partial\phi}=0$, $\frac{\partial\tilde{q}_{2n}^{L-h}}{\partial\phi}=0$, *and* $\frac{\partial\tilde{q}_{2n}^{H-h}}{\partial\phi}=0$;

(3)
$\frac{\partial\left(\tilde{q}_{2n}^{L-l}+q_{2n}^{L-l}\right)}{\partial\phi}=\frac{\partial\left(\tilde{q}_{2n}^{H-l}+q_{2n}^{H-l}\right)}{\partial\phi}<\frac{\partial\left(\tilde{q}_{2n}^{L-h}+q_{2n}^{L-h}\right)}{\partial\phi}=\frac{\partial\left(\tilde{q}_{2n}^{H-h}+q_{2n}^{H-h}\right)}{\partial\phi}=0$

Proposition 3 indicates that the remanufacturing promotion program hurts the market share of new products on the total market. Specially, on the replacement segment, subsidize the remanufacturing always deters the new products consumption. On the primary segments, the subsidy program performs a non-negative effect on new products consumption.

We use figure 4a and figure 4b to describe this phenomenon. In figure 4a, it can be found that with ϕ increases, Point B moves left and Point A remains the same. This means that the market share of remanufactured products shrinks on the primary market. In figure 4b, where Point A' moves left and Point B' moves right. This means that the remanufactured market share enlarges however the market share of new products shrinks on the replacement market. This explains why the subsidy program is not effective but harmful on the primary segment.

However, by observing Table A1, we find that when the manufacturer chooses to price the new product sufficiently high, this phenomenon no longer appears. According to the analysis, we conclude that the total consumption of remanufactured products on the entire market is $\partial Q_{2r}^{L-l}/\partial\phi=\partial\left(\bar{q}_{2r}^{L-l}+q_{2r}^{L-l}\right)/\partial\phi=\gamma/\left[2(1-\rho)(\rho-1+\gamma)\right]>0$ (i.e., $\left|\partial q_{2r}^{L-l}/\partial\phi\right|>\left|\partial\bar{q}_{2r}^{L-l}/\partial\phi\right|$), and this suggests that although the remanufacturing consumption on the primary market decreases with government subsidy, the total remanufacturing quantity still increases with the subsidy. We have checked the effectiveness of the program on consumption. Next, we will investigate how government subsidy affects the firm's profit.

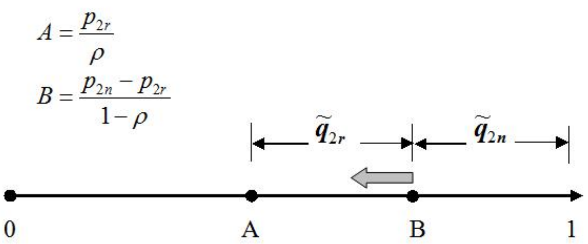

Figure 4a. The change of demand on the replacement market when increases

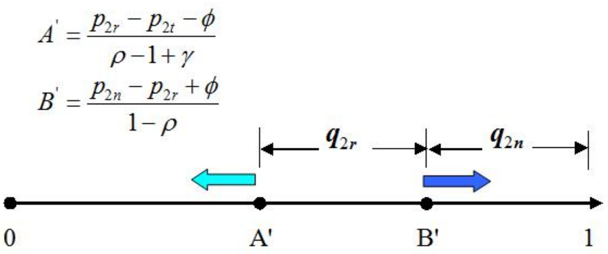

Figure 4b. The change of demand on the primary market when increases

C. The impacts of market potential on remanufacturing demands

We first focus on studying model L-l, where both the two segments are covered by the two differentiated products. With the first order conditions, we derive that

Proposition 2.

(i) *In scenario L-l, the market size of primary consumers* (Δ) *plays a positive role in promoting the consumption of remanufactured products through trade-ins.*

(ii) *In scenarios L-h, H-l and H-h, the market size of primary consumers* (Δ) *has nothing to do with the consumption of remanufactured products through trade-ins.*

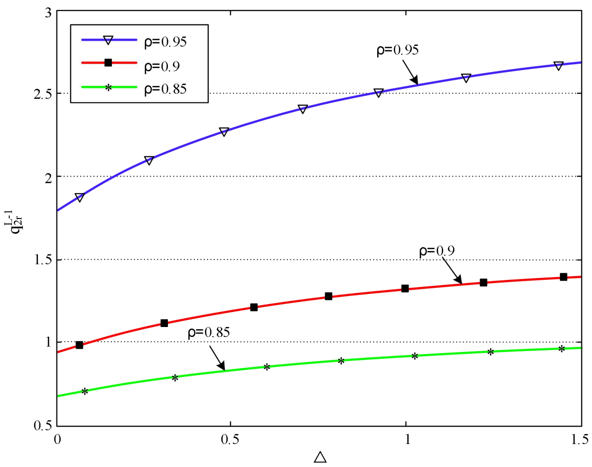

Figure 5. The impact of market growth on the remanufacturing consumption.

Proposition 2. (i) indicates that increasing the market size of primary consumers (Δ) helps promoting the consumption of remanufactured products from the replacement segment. Figure 5 shows that with Δ increasing, q_{2r}^{L-l} increases. Figure 5 also informs us that when consumers have more preference on remanufactured products, q_{2r}^{L-l} increases faster with Δ. It is interesting as intuitively one might think that the choice of primary consumer segment does not influence replacement consumer segment. Notice that when the market size of primary consumers (Δ) is zero, or when neglecting the primary segment, the two differentiated products' demand relies merely on the replacement segment.

However, when the primary segment is taken into consideration and the selling price of remanufactured product is not high enough, the new product's selling price increases faster than the remanufactured product's selling price, i.e., $\partial p_{2n}/\partial\Delta = \phi\big/\left[2(1+\Delta)^2\right] > 0 = \partial p_{2r}/\partial\Delta$ for the primary segment, and we can obtain a similar finding showing that $\partial(p_{2n} - p_{2t})/\partial\Delta = \phi\big/\left[2(1+\Delta)^2\right] > 0 = \partial(p_{2r} - p_{2t})/\partial\Delta$ for the replacement segment. This notifies that with Δ increasing, the actual price of new product for both the primary and replacement segments increases faster than the selling price of the remanufactured product, which induces the consumers to buy more remanufactured products. This fact explains Proposition 2. Since the aim of this promotion program is to stimulus remanufacturing consumption, we will show the varying effect in the next section. Proposition 2. (ii) shows that the market size of primary consumers (Δ) has no influence on the consumption of remanufactured products from the replacement segment in the scenario of Model *L-h*, Model *H-l* and Model *H-h*. That is to say, the market size of primary consumers (Δ) only affects the consumption of remanufactured products from the replacement segment in the scenario of Model *L-l*.

V. THE IMPACTS ON FIRM'S PROFITABILITY

Intuitively, the promotion plan stimulates the consumers' willingness of buying remanufactured products. As the new and remanufactured products performs a different profit margin, then the increased demands of remanufactured products might not be always helpful on improving the firm's revenue.

Proposition 4.

(i) *In scenario L-l, the manufacturer's profit function is parabola and opens upward on parameter* ϕ, *that is, with* ϕ *increasing,* Π^{L-l} *first decreases and then increases. Specially, when*

$$\bar{\phi} = \frac{-\Delta\rho c_n + \Delta\rho\psi - \Delta c_n\gamma + \Delta\gamma c_r + \Delta c_n - \Delta\psi - \psi - c_n\rho + c_n + \psi\rho + \gamma(c_r - c_n)}{\Delta(1-\rho) + \gamma}$$

Π^{L-l} *reaches its minimum value* $\min \Pi^{L-l}(\phi) = \Pi^{L-l}(\bar{\phi})$;

(ii) *When* $\bar{\phi} \le 0$ *or when* $c_r < \bar{c}_r = \left[(1-\rho)(\psi - c_n) + c_n\gamma\right]/\gamma$ *equivalently, for* $\phi > 0$, Π^{L-l} *always increases when government subsidy* (ϕ) *increases.*

Proposition 4 suggests that with government subsidy increasing, the manufacturer's profit in the scenario of *L-l* does not always increase, and the trend of Π^{L-l} on ϕ depends on a key parameter $\bar{\phi}$. This phenomenon can be explained by the fact that in the early stage of government subsidy on remanufacturing through trade-in, a portion of potential replacement consumers who are originally intended to buy new products will switch to buy remanufactured products because of the subsidy. When the unit profit of selling a remanufactured product is low or the remanufacturing cost is high ($c_r > \bar{c}_r = \left[(1-\rho)(\psi - c_n) + c_n\gamma\right]/\gamma$), and the unit profit of selling a new product is high or the cost of producing a new product is low ($c_n < \bar{c}_n = \left[\gamma c_r - (1-\rho)\psi\right]/(\rho - 1 + \gamma)$), at this stage the manufacturer's total profit will decrease with government subsidy ϕ.

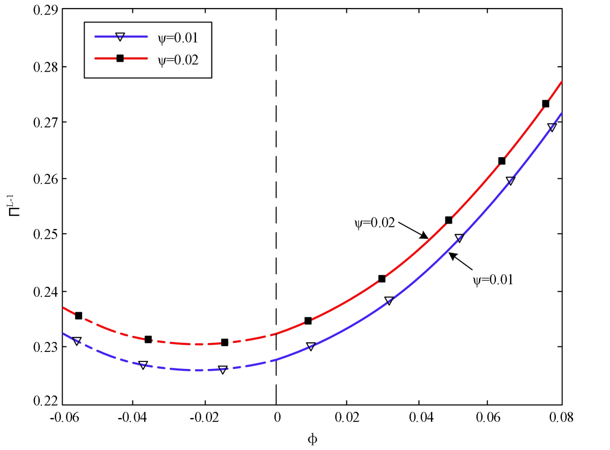

Figure 6. The effect of government subsidy on firm's profit. (where $\rho=0.95$, $c_n=0.05$, $c_r=0.03$, $\gamma=0.8$ and $\Delta=0.2$.)

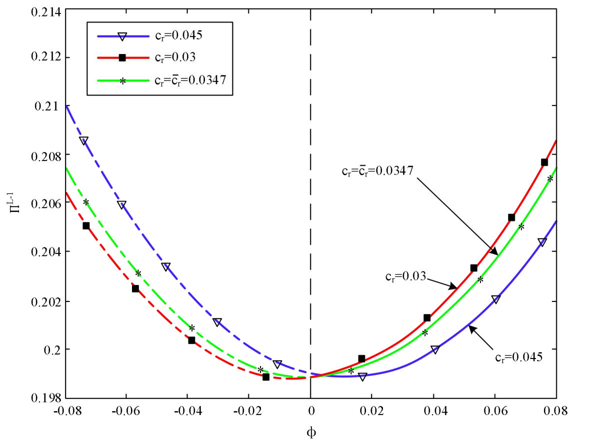

Figure 7. The effect of parameter c_r and ϕ on firm's profit. (where $\rho=0.75$, $c_n=0.05$, $\bar{c}_r=0.0347$, $\gamma=0.8$ and $\Delta=0.1$)

Further, when the production cost of a remanufactured product is low, i.e., $c_r<\bar{c}_r=\left[(1-\rho)(\psi-c_n)+c_n\gamma\right]/\gamma$, Π^{L-l} will always increase with ϕ. In Figure 8, region R show the area where firm profit always increases when the subsidy level increases. While in region S, the impacts on the profit depends on actual value of the subsidy ϕ. Notice that $\partial\bar{\phi}/\partial\psi=\left[(\rho-1)(1+\Delta)\right]/\left[\Delta(1-\rho)+\gamma\right]<0$, which implies that the threshold $\bar{\phi}$ decreases when the salvage value ψ increases. In other words, when ψ increases, the direct income of the manufacturer from the collection activity ($(\psi-p_{2t})=(\psi-1+\phi+\gamma)/2$) increases, and the threshold $\bar{\phi}$ occurs in advance. For the profit function of scenario *H-l* (see Appendix B), we obtain similar findings as

$$\frac{\partial^2\Pi^{H-l}}{\partial\phi^2}=-\frac{\rho\gamma}{8\rho(\rho-1)(\rho-1+\gamma)}>0$$

Here, $\bar{\phi}=\left[\rho c_n-\psi\rho-\rho^2 c_n+\psi\rho^2+\gamma\rho(c_r-c_n)\right]/\rho\gamma$, still we can observe that $\partial\bar{\phi}/\partial\psi=(\rho-1)/\gamma<0$, namely that when ψ increases, the manufacturer's direct income from trade-in ($(\psi-p_{2t})=(\psi-1+\phi+\gamma)/2$) will increase, and the key threshold $\bar{\phi}$ becomes smaller. The main findings in Proposition 4 are depicted in Figures 6 and 7. From Figure 6, it can be found that with salvage value ψ increasing, Π^{L-l} increases as $\bar{\phi}$ deceases.

From Figure 7, we can find that when the remanufacturing cost $c_r=0.03<\bar{c}_r=0.0347$, Π^{L-l} always increases with ϕ, and when $c_r=0.045>\bar{c}_r=0.0347$, Π^{L-l} first decreases and then increases when government subsidy ϕ increases. This finding indicates that when the cost of remanufacturing is low, the program will also ways be beneficial to the firm. Because tax imposed by the government can be an important part of production, thus reducing remanufactured product's added value tax can be a meaningful tool to promote remanufacturing.

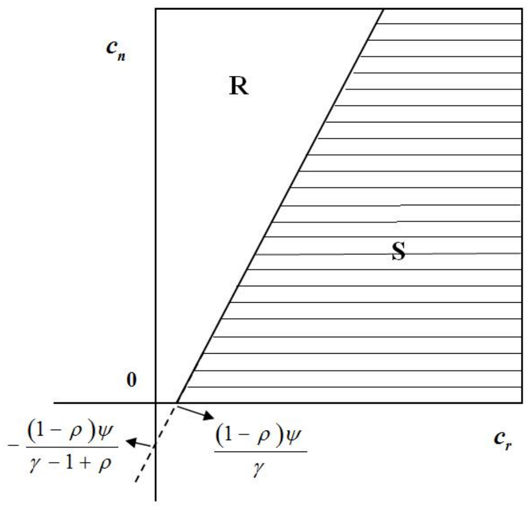

Figure 8. The relationship of costs and the firm's direct income in trade-in

On the replacement market, we need to think about the following questions: Does the manufacturer always benefit directly from the collection activities in these four cases? Is it possible that the manufacturer collects at a deficit in order to attract the trade-ins consumers? To answer the two questions, some results are as following:

Proposition 5.

(i) *When* $\psi\geq\bar{\psi}=c_r/[4(1-\rho)]$ *, if the relevant condition is met, i.e.,* $1-\gamma-\psi\leq\phi\leq1-\gamma+3\psi+\frac{c_r}{-1+\rho}$*, the manufacturer's direct income from trade-in is positive, i.e.,* $(\psi-p_{2t})\geq0$*; otherwise, we have* $(\psi-p_{2t})<0$.

(ii) *When* $\psi<\bar{\psi}=c_r/[4(1-\rho)]$*, the manufacturer's direct income from trade-in is negative all the time, i.e.,* $(\psi-p_{2t})<0$.

Proposition 5 implies that the value of government subsidy plays an important role in the manufacturer's direct income in the trade-in activity, and it suggests that the manufacturer does not always benefit directly from the used product collection. When $(\psi-p_{2t})<0$, the manufacturer even collects at a loss for a unit collection. However, the manufacturer does not have to be in deficit. The manufacturer's loss in the collection activity can be offset by the selling of new and remanufactured products.

By observing the values of $(\psi - p_{2t})$ in the four scenarios, it can be found that the direct incomes all increase with unit salvage value (ψ), which is one of the reasons why firms are willing to implement trade-in transactions. In Figure 9, the shadow part indicates that the direct income per unit of the manufacturer in the trade-in is positive, and the other blank areas mean that the unit direct income of the manufacturer in the trade in is negative. Next, we answer the question about how government subsidy affects the (re)manufacturer's profit.

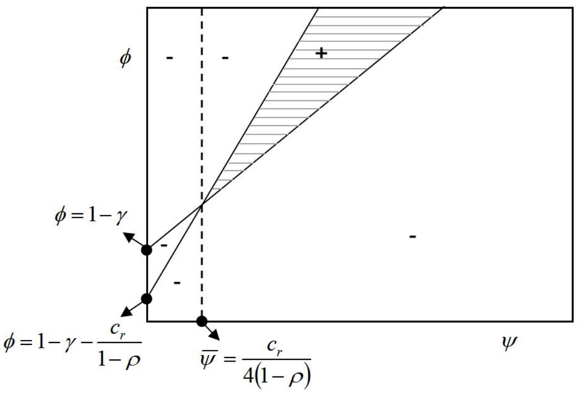

Figure 9. The direct income of firm when ϕ and ψ varies

In the next section, we will investigate how the consumer's preference, production costs, and government subsidy affect the manufacturer's pricing strategy. The manufacturer's decision depends on which scenario yields a larger profit. We choose to study the decision maker's trade-off between scenarios *L-l* and *H-h* as they respectively model the condition of fully covered and partially covered market: in scenario *H-h*, the manufacturer applies an extreme pricing strategy and puts emphasis on the remanufacturing market, namely pricing the new product very high to sell remanufactured products only. By comparing the profits of the two scenarios, we can derive the following proposition.

Proposition 6.

(i) *When* $\rho-1+c_n-c_r>0$, *if* $\chi>0$ *(with* χ *defined below), the firm will adopt an extreme strategy that only sells remanufactured product if* $0<\phi<\phi_1^*$ *is satisfied; and will adopt a moderate strategy that sells both new and remanufactured product if* $\phi \ge \phi_1^*$; *when* $\chi \le 0$, *if* $\phi>0>\phi_1^*>\phi_2^*$, *the firm will adopt a moderate strategy that sells both new and remanufactured product.*

(ii) *When* $\rho-1+c_n-c_r \le 0$, *if* $\chi>0$, *the firm will adopt an extreme strategy when* $0<\phi<\phi_1^*$, *and will adopt a moderate strategy when* $\phi \ge \phi_1^*$; *if* $\chi \le 0$, *the firm will choose a moderate pricing strategy when* $\phi \ge \phi_1^*$ *or* $0 \le \phi \le \phi_2^*$ *is satisfied, and an extreme strategy when* $\phi_2^* < \phi < \phi_1^*$.

Where $\phi_1^* = -(\rho-1+c_n-c_r)(1+\Delta)+\dfrac{(1-\rho)\sqrt{-2\Delta\rho(c_r-\rho)(1+\Delta)}}{\rho}$,

$$\phi_2^* = -(\rho-1+c_n-c_r)(1+\Delta)-\frac{(1-\rho)\sqrt{-2\Delta\rho(c_r-\rho)(1+\Delta)}}{\rho}$$

and χ *is defined as*

$$\chi = 2\Delta(\rho-1)^2(\rho-c_r)-\rho(\rho-1+c_n+c_r)^2(1+\Delta)$$

In Proposition 6, we show that how the manufacturer chooses its pricing strategy according to the set value of government subsidy. As (c_n-c_r) stands for the unit cost saving of remanufacturing, and $(1-\rho)$ represents the difference of consumers' acceptance of new and remanufactured product, the term $\rho-1+c_n-c_r$ can be regarded as the difference of consumer acceptance margin and cost saving, and $\rho-1+c_n-c_r>0$ when cost saving is larger. The following two figures illustrate the decision interval of the manufacturer.

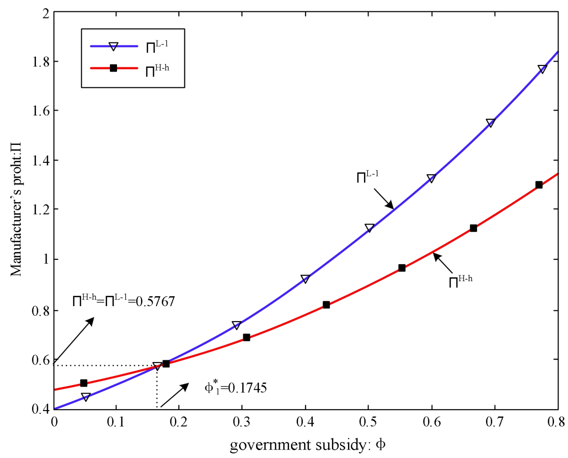

Figure 10. The effect of parameter ϕ on firm's pricing strategy. (where $\rho=0.8$, $c_n=0.5$, $c_r=0.15$, $\gamma=0.5$, $\psi=0.1$ and $\Delta=2$)

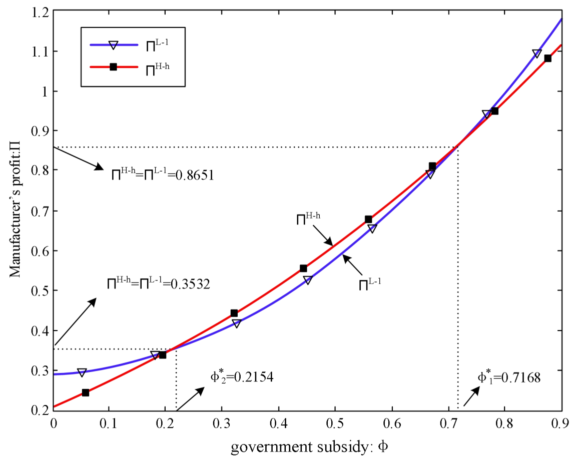

Figure 11. The effect of parameter ϕ on firm's pricing strategy. (where $\rho=0.6$, $c_n=0.05$, $c_r=0.045$, $\gamma=0.9$, $\psi=0.1$ and $\Delta=0.18$)

Figure 10 indicates that when cost saving is larger than consumer acceptance margin and subsidy level is low, i.e., $\phi<\phi_1^*=0.1745$, producing and selling remanufactured product only will be a better strategy than selling both the new and remanufactured product. Figure 11 shows that when cost saving is smaller than consumer acceptance margin and subsidy level is low (i.e., $\phi<\phi_2^*=0.2154$) or large enough (i.e., $\phi > \phi_1^* = 0.7168$), selling both new and remanufactured product will be a better strategy.

VI. Conclusion

In this paper, we work on the optimization of remanufacturing decisions under government subsidy. Being different from subsidy in CLSC studied in existing literature, the considered government program is merely focused on the trade-ins with remanufactured products. To investigate the effect of government subsidy, we established profit maximizing models considering consumers with different types (primary and replacement consumers) for new and remanufactured products. We have the following important findings:

(1) Government subsidy does not always promote remanufacturing consumption;

(2) The subsidy program might be harmful to the firm's profit when the cost advantage of remanufacturing is not high.

(3) Remanufacturing of the replacement consumers is highly correlated with the market potential of the primary market.

It has been found that the government subsidy program plays a negative role in the consumption of remanufactured product on the primary market although it has been proved to be effective in promoting remanufacturing consumption on the replacement segment. Results show that whether the manufacturer's profit is positively influenced by the program depends on the production cost of remanufacturing, and the manufacturer's profit will always increase with government subsidy when the remanufacturing cost is low enough. Besides, when the remanufactured product's price is not that high, with the market size of primary consumers increasing, the consumption of remanufactured products through trade-ins increases. Results also suggest that to profit more on the selling side, the manufacturer does not always benefit directly from collecting the used product. We also investigate how the manufacturer makes its strategic selection on pricing strategy according to the subsidy level. To obtain direct managerial insights, we modeled our research in a single period horizon. When the remanufacturing is constrained by consumers' early-stage consumption, it is meaningful and worthwhile to expand our model into a two-period planning horizon.

Appendix

Appendix A.

Proof of Proposition 1.

Proof. First we substitute $q_{2n} = 1 - \dfrac{p_{2n} - p_{2r} + \phi}{1-\rho}$, $q_{2r} = \dfrac{p_{2n} - p_{2r} + \phi}{1-\rho} - \dfrac{p_{2r} - p_{2t} - \phi}{\rho - 1 + \gamma}$, $\tilde{q}_{2n} = \Delta\left(1 - \dfrac{p_{2n} - p_{2r}}{1-\rho}\right)$ and $\tilde{q}_{2r} = \Delta\left(\dfrac{\rho p_{2n} - p_{2r}}{(1-\rho)\rho}\right)$ into the profit function and solve the first order conditions on p_{2n}, p_{2t} and p_{2r}. We have

$$\frac{\partial\Pi^{L\text{-}l}(p_{2n},p_{2r},p_{2t})}{\partial p_{2n}} = \frac{(1+\Delta)(1-\rho-2p_{2n}+2p_{2r}+c_n-c_r)-\phi}{1-\rho} = 0$$

$$\frac{\partial\Pi^{L\text{-}l}(p_{2n},p_{2r},p_{2t})}{\partial p_{2r}} = \frac{2p_{2n}-c_n+\psi-p_{2t}}{1-\rho} + \frac{\gamma(\phi-\psi-2p_{2r}+c_r)+p_{2t}(1-\rho+\gamma)}{(1-\rho)(\rho-1+\gamma)} + \Delta\frac{p_{2n}-c_n}{1-\rho} + \Delta\frac{\rho p_{2n}-2p_{2r}+c_r}{(1-\rho)\rho} = 0$$

$$\frac{\partial(p_{2n},p_{2r},p_{2t})}{\partial p_{2t}} = -\frac{1-\rho+p_{2r}-\phi}{1-\rho} + \frac{-\gamma(\phi-p_{2r})+(1-\rho)(\psi+p_{2r}-2p_{2t}-c_r)}{(1-\rho)(\rho-1+\gamma)} = 0$$

Notice that the decision problem above is a quadratic optimization problem with linear constraints. Because the Hessian matrix is negatively definite, by solving the system of the first order conditions, we can show that the unconstrained solutions are:

$$p_{2n} = \frac{1-\phi+\Delta+\Delta c_n + c_n}{2(1+\Delta)}$$

$$p_{2r} = \frac{\rho + c_r}{2}$$

$$p_{2t} = \frac{1-\phi-\gamma+\psi}{2}$$

Recall that the precondition of Model *L-l* is $p_{2r}/\rho \le p_{2n} \le p_{2r} + 1 - \rho$ and

$$\frac{\gamma(\phi - p_{2r}) + p_{2t}(1-\rho)}{(\rho - 1 + \gamma)} < p_{2n} < 1 - \rho + p_{2r} - \phi.$$

Comparing the two conditions we have:

$$\max\left\{\frac{\gamma(\phi - p_{2r}) + p_{2t}(1-\rho)}{(\rho - 1 + \gamma)}, p_{2r}/\rho\right\} < p_{2n} < 1 - \rho + p_{2r} - \phi.$$

Substituting $p_{2n} = \dfrac{1-\phi+\Delta+\Delta c_n + c_n}{2(1+\Delta)}$, $p_{2r} = \dfrac{\rho + c_r}{2}$ and $p_{2t} = \dfrac{1-\phi-\gamma+\psi}{2}$ into these inequalities then we find that when $c_r > c_{r-1} = \dfrac{\rho+\phi-1+\Delta(\rho+2\phi-1)+(1+\Delta)c_n}{1+\Delta}$, we have $p_{2n} < 1-\rho+p_{2r}-\phi$. When $c_r < c_{r-2} = \dfrac{\rho(c_n+\Delta c_n - \phi)}{1+\Delta}$, we have the following result, $p_{2n} > \dfrac{p_{2r}}{\rho}$, in addition, when $c_r < c_{r-3} = \dfrac{\gamma(\phi+2\Delta\phi)+(\rho-1)(\Delta\phi-\psi-\Delta\psi)+(1+\Delta)(\gamma+\rho-1)c_n}{\gamma(1+\Delta)}$, we have $p_{2n} > \dfrac{\gamma(\phi - p_{2r}) + p_{2t}(1-\rho)}{(\rho - 1 + \gamma)}$. When these conditions are satisfied, new and remanufactured products cover both the primary and replacement markets.

Proof of Proposition 2.

Proof. In model *L-l*, the demand for remanufactured products from the replacement consumers is solved as

$$q_{2r}^{L-l} = \frac{(p_{2n} - p_{2t})(\rho-1) + \gamma(p_{2n} - p_{2r} + \phi)}{(\rho - 1 + \gamma)(1-\rho)} = \frac{\begin{pmatrix}\Delta\left(2\gamma\phi - \rho\psi - \phi + \varphi - \gamma c_r + \rho(\phi + c_n) - c_n(1+\gamma)\right) \\ +\varphi(1-\rho) + \gamma\phi - \gamma c_r + c_n(\psi + \gamma - 1)\end{pmatrix}}{2(1+\Delta)(\rho - 1 + \gamma)(1-\rho)}$$

Derive the first order condition of q_{2r}^{L-l} on Δ, then we have

$$\frac{\partial q_{2r}^{L-l}}{\partial\Delta} = -\frac{\phi}{2(1+\Delta)^2(-1+\rho)} > 0$$

In Model *L-h,* the demand for remanufactured products from the replacement consumers is solved as

$$q_{2r}^{L-h}=\frac{\rho+\psi-1-c_r+\gamma+\phi}{2(\rho-1+\gamma)}$$

Derive the first order condition of q_{2r}^{L-h} on Δ, then we have

$$\frac{\partial q_{2r}^{L-h}}{\partial\Delta}=0$$

The proof of Model *H-l* and Model *H-h* is similar to that of Model *L-h,* therefore we choose to omit it.

Proof of Proposition 3.

Proof. To derive the first order condition of q_{2r}^{L-l} on ϕ, we have:

$$\frac{\partial q_{2r}^{L-l}}{\partial\phi}=\frac{2\Delta+1}{2(1+\Delta)(1-\rho)}+\frac{1}{2(\rho-1+\gamma)}=-\frac{2\Delta\gamma-\Delta+\gamma+\Delta\rho}{2((1+\Delta)(-1+\rho)(\rho-1+\gamma))}$$

$$>-\frac{\Delta(\gamma-1+\rho)+\gamma}{2((1+\Delta)(-1+\rho)(\rho-1+\gamma))}>0$$

The proofs of the other three scenarios can be obtained similarly. Next, we try to investigate how government subsidy influences the remanufacturing demand from the primary segment. The demand can be calculated as below

$$\tilde{q}_{2r}^{L-l}=\Delta\left(\frac{\rho p_{2n}-p_{2r}}{(1-\rho)\rho}\right)=\frac{\Delta(-\rho\phi+\Delta\rho c_n+c_n\rho-c_r-\Delta c_r)}{(1+\Delta)\rho(1-\rho)}.$$

To derive the first order conditions, we have:

$$\frac{\partial\tilde{q}_{2r}^{L-l}}{\partial\phi}=-\frac{\Delta\rho}{2\rho(1+\Delta)(1-\rho)}<0\cdot$$

For the total remanufacturing consumption, we have:

$$\frac{\partial\left(\tilde{q}_{2r}^{L-l}+q_{2r}^{L-l}\right)}{\partial\phi}=\frac{\partial\left(\tilde{q}_{2r}^{H-l}+q_{2r}^{H-l}\right)}{\partial\phi}=-\frac{\gamma}{2(\rho-1+\gamma)(-1+\rho)}>0;$$

$$\frac{\partial\left(\tilde{q}_{2r}^{L-h}+q_{2r}^{L-h}\right)}{\partial\phi}=\frac{\partial\left(\tilde{q}_{2r}^{H-h}+q_{2r}^{H-h}\right)}{\partial\phi}=\frac{1}{2(\rho-1+\gamma)}>0$$

By comparing the term $\frac{\gamma}{2(\rho-1+\gamma)(1-\rho)}$ with $\frac{1}{2(\rho-1+\gamma)}$ with the assumption $(\rho-1+\gamma)>0$, we can prove (3).

Proof of Proposition 4.

Proof. Substituting $p_{2n}=\frac{1-\phi+\Delta+\Delta c_n+c_n}{2(1+\Delta)}$, $p_{2r}=\frac{\rho+c_r}{2}$ and $p_{2t}=\frac{1-\phi-\gamma+\psi}{2}$ into Eq. (3), we can obtain the manufacturer's profit under scenario *L-l* Π^{L-l} (see Appendix B). Given $0<\rho<1$ and $\rho>1-\gamma$, after deriving the second order conditions, we have

$$\frac{\partial\Pi^{L-l}}{\partial\phi}=\frac{\gamma(1+\Delta)c_r-\gamma\phi+(\rho-1)(\psi+\Delta(\phi+\psi))-(1+\Delta)(\gamma+\rho-1)c_n}{2(1+\Delta)(\rho-1)(\rho-1+\gamma)}$$

$$\frac{\partial^2\Pi^{L-l}}{\partial\phi^2}=\frac{\Delta\rho(\rho-1)-\gamma}{4\rho(1+\Delta)(\rho-1)(\rho-1+\gamma)}>0$$

By solving $\partial\Pi^{L-l}/\partial\phi=0$, we can obtain $\overline{\phi}$. When $\overline{\phi}\le 0$, Π^{L-l} exhibits a trend as stated in (1) where Π^{L-l} first decreases and then increases with government subsidy ϕ. Because ϕ must be positive, thus, when $\phi\ge\max(0,\overline{\phi})$, Π^{L-l} always increases when ϕ increases. Then Proposition 4 can be proved.

Proof of Proposition 5.

Proof. Considering the four scenarios, we derive the direct income of the manufacturer in the trade-in activity as below:

$$(\psi-p_{2t})^{L-l}=(\psi-p_{2t})^{H-l}=(\psi-p_{2t})^{H-h}=\psi-\frac{1-\phi-\gamma+\psi}{2}=\frac{\psi-1+\phi+\gamma}{2},$$

$$(\psi-p_{2t})^{L-h}=\psi-\frac{-c_r+(1-\rho)(1-\gamma-\phi+\psi)}{2(\rho-1)}=\frac{(\rho-1)(1-\gamma-\phi+3\psi)+c_r}{2(\rho-1)}$$

To ensure $(\psi-p_{2t})\ge 0$, it requires that $\phi\ge 1-\gamma-\psi$ and $\phi\le 1-\gamma+3\psi-\frac{c_r}{1-\rho}$. If $1-\gamma-\psi-(1-\gamma+3\psi-c_r/(1-\rho))\le 0$ or equivalently $\psi\ge\frac{c_r}{4(1-\rho)}$, we have $(\psi-p_{2t})\ge 0$ when $1-\gamma-\psi\le\phi\le 1-\gamma+3\psi-\frac{c_r}{1-\rho}$ is satisfied. Similarly, we have $(\psi-p_{2t})<0$ when $\phi>1-\gamma+3\psi-\frac{c_r}{1-\rho}$ or $\phi<1-\gamma-\psi$ is satisfied. Moreover, when $\psi<\frac{c_r}{4(1-\rho)}$, i.e., $1-\gamma-\psi-(1-\gamma+3\psi-c_r/(1-\rho))>0$, then we have $(\psi-p_{2t})<0$ all the time.

Proof of Proposition 6.

Proof. To compare the profit under Model *H-h* and Model *L-l*, we define $\Pi^{Hh-Ll}(\phi)=\Pi^{H-h}-\Pi^{L-l}$. By solving the second order condition of $\Pi^{Hh-Ll}(\phi)$ on ϕ, we have $\partial^2\Pi^{Hh-Ll}(\phi)/\partial\phi^2=1/[2(1+\Delta)(\rho-1)]<0$. Thus, $\Pi^{Hh-Ll}(\phi)$ will present as a parabola opening downward. Further, solving the roots of $\Pi^{Hh-Ll}(\phi)=0$, we have

$$\phi_1^*=\frac{-\rho(\rho-1+c_n-c_r)(1+\Delta)+\sqrt{-2\Delta\rho(\rho-1)^2(c_r-\rho)(1+\Delta)}}{\rho},$$

$$\phi_2^*=\frac{-\rho(\rho-1+c_n-c_r)(1+\Delta)-\sqrt{-2\Delta\rho(\rho-1)^2(c_r-\rho)(1+\Delta)}}{\rho}$$

We consider two cases: case 1, $\rho-1+c_n-c_r>0$; case 2, $\rho-1+c_n-c_r\le 0$.

Case 1, when $\rho-1+c_n-c_r>0$. If $\chi>0$, namely, the numerator of ϕ_1^* is positive. Then we have $\phi_1^*>0$ and $\phi_2^*<0$. As government subsidy must be presented as a positive value, thus, when $0<\phi<\phi_1^*$, $\Pi^{Hh-Ll}(\phi)>0$, and when $\phi\ge\phi_1^*>0$, $\Pi^{Hh-Ll}(\phi)\le 0$. If $\chi\le 0$, then we can conclude that $\phi_2^*<\phi_1^*<0$, then, for $\phi>0>\phi_1^*>\phi_2^*$, we have $\Pi^{Hh-Ll}(\phi)<0$ or $\Pi^{H-h}<\Pi^{L-l}$

Case 2, when $\rho-1+c_n-c_r\le 0$. If $\chi>0$, then we have $\Pi^{Hh-Ll}(\phi)>0$ when $0<\phi<\phi_1^*$, and $\Pi^{Hh-Ll}(\phi)\le 0$ when $\phi\ge\phi_1^*>0$ is satisfied. If $\chi\le 0$, we have $\phi_1^*>\phi_2^*>0$, and then we have $\Pi^{Hh-Ll}(\phi)>0$ when $\phi_2^*<\phi<\phi_1^*$, and $\Pi^{Hh-Ll}(\phi)\le 0$ when $\phi\ge\phi_1^*$ or $0\le\phi\le\phi_2^*$ is satisfied.

TABLE A1.
OPTIMAL PRICING OF DIFFERENT SCENARIOS

Scenarios	Case $\boldsymbol{L}$	Case $\boldsymbol{H}$
Case $\boldsymbol{l}$	$\boldsymbol{p}_{2n}=\frac{1-\phi+\Delta+\Delta\boldsymbol{c}_n+\boldsymbol{c}_n}{2(1+\Delta)}$ $\boldsymbol{p}_{2r}=\frac{\rho+\boldsymbol{c}_r}{2}$ $\boldsymbol{p}_{2t}=\frac{1-\phi-\gamma+\psi}{2}$	$\boldsymbol{p}_{2n}=\frac{1-\phi+\boldsymbol{c}_n}{2}$ $\boldsymbol{p}_{2r}=\frac{\rho+\boldsymbol{c}_r}{2}$ $\boldsymbol{p}_{2t}=\frac{-\phi+1-\gamma+\psi}{2}$
Case $\boldsymbol{h}$	$\boldsymbol{p}_{2n}=\frac{\boldsymbol{c}_r-\boldsymbol{c}_n+\boldsymbol{c}_n\rho-1+\rho}{2(-1+\rho)}$ $\boldsymbol{p}_{2r}=\frac{\rho(\rho-1+\boldsymbol{c}_r)}{2(-1+\rho)}$ $\boldsymbol{p}_{2t}=\frac{-\boldsymbol{c}_r+(1-\rho)(1-\gamma-\phi+\psi)}{2(\rho-1)}$	$\boldsymbol{p}_{2r}=\frac{\rho+\boldsymbol{c}_r}{2}$ $\boldsymbol{p}_{2t}=\frac{-\phi+1-\gamma+\psi}{2}$

Appendix B:

B1. The closed form of profit of the firm in Model *L-l*:

$$\Pi^{L-l}=\frac{\begin{pmatrix}\rho(\gamma^2(1+\Delta)(\rho-1)+\gamma(1+\Delta^2(\rho-1)+\rho^2-\phi^2+2\rho(\psi-1)-2\psi+\Delta(\rho^2+2\psi-\rho))\\+(\rho-1)(\Delta^2(\rho-1)+\psi(-2+2\rho+2\phi+\psi)+\Delta((\rho-1)+\phi^2-2\psi+2\rho\psi+2\phi\psi+\psi^2)))\\-(\gamma(1+\Delta)^2+(1+2\Delta)(\rho-1))\rho+2(1+\Delta)\rho(\gamma\phi+\psi-\rho\psi)\boldsymbol{c}_r-(1+\Delta)(\gamma\rho+\Delta(\rho-1+\gamma))\\-2(1+\Delta)\rho(\rho-1+\gamma)\boldsymbol{c}_n(-1+\Delta(\rho-1)+\rho+\phi-(1+\Delta)\boldsymbol{c}_r)\end{pmatrix}}{4\rho(1+\Delta)(\rho-1)(\rho-1+\gamma)}$$

B2. The closed form of profit of the firm in Model *H-l*:

$$\Pi^{H-l}=\frac{\begin{pmatrix}\rho(-\gamma\phi+(\rho-1)\psi)-2\rho(\rho-1+\gamma)\boldsymbol{c}_n(\rho-1+\phi-\boldsymbol{c}_r)-2(\Delta(\rho-1)(\rho-1+\gamma))\boldsymbol{c}_r\\-\rho(-\gamma^2(-1+\rho)+\gamma(-1+2\rho-\rho^2+\Delta(2-3\rho+\rho^2)+\phi^2+2\psi-2\rho\psi)\\+(\rho-1)(\Delta(2-3\rho+\rho^2)-\psi(-2+2\rho+2\phi+\psi)))-\rho(\rho-1+\gamma)\\+(-\gamma\rho+\Delta(-1+\rho)(-1+\gamma+\rho))\end{pmatrix}}{4\rho(\rho-1)(\rho-1+\gamma)}$$

B3. The closed form of profit of the firm in Model *L-h*:

$$\Pi^{L-h}=\frac{\begin{pmatrix}(\rho-1)^2(\gamma^2+\Delta(\rho-1)+(\rho-1+\phi+\psi)^2+\gamma(\Delta+2(\rho-1+\phi+\psi)))\\-\Delta(\rho-1)(-1+\gamma+\rho)-2\Delta(\rho-1)(-1+\gamma+\rho)\boldsymbol{c}_n(\rho-1-\boldsymbol{c}_r)\\-2(\rho-1)^2(-1+\gamma+\rho+\phi+\psi)\boldsymbol{c}_r+(\rho-1)^2-\Delta(-1+\gamma+\rho)\end{pmatrix}}{4(\rho-1)^2(\rho-1+\gamma)}$$

B4. The closed form of profit of the firm in Model *H-h*:

$$\Pi^{H-h}=\frac{\begin{pmatrix}\rho(\gamma^2-\Delta(2-3\rho+\rho^2)+(\rho+\phi+\psi-1)^2+\gamma(2(\rho-1+\phi+\psi)-\Delta(-2+\rho)))\\-2(\Delta(\gamma+\rho-1)+\rho(\gamma-1+\rho+\phi+\psi))\boldsymbol{c}_r+(\rho+\Delta(\gamma+\rho-1))\end{pmatrix}}{4\rho(\rho-1+\gamma)}$$

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