RAIRO-Oper. Res. 56 (2022) 1259–1281
https://doi.org/10.1051/ro/2022041

RAIRO Operations Research
www.rairo-ro.org

OPTIMAL CHANNEL SELECTION OF REMANUFACTURING FIRMS WITH CONSIDERING ASYMMETRIC INFORMATION IN PLATFORM ECONOMY

Kaiying Cao[1], Yunyi Su[2], Yuqiu Xu[2,*] and Jia Wang[3]

Abstract. With the rapid development of e-commerce platforms, and considering that online return rate is relatively high and third-party stores on e-commerce platforms need to adopt third-party logistics, thus remanufacturing firms face the challenge of deciding whether to enter e-commerce platforms. To address this challenge, our paper considers a remanufacturing firm, an e-commerce platform, and a third-party logistics provider. Moreover, according to whether the remanufacturing firm enters the platform and whether the information is symmetrical, we develop three theoretical models: Model NP (the firm doesn't enter platform), Model YP (the firm enters platform with symmetric information) and Model YA (the firm enters platform with asymmetric information). Some main insights are obtained. We find that whether remanufacturing firms should enter the platform depends not only on the annual service fee charged by the platform but also on the carbon tax price set by the government. Interestingly, improved consumers' satisfaction with online remanufactured products is not necessarily conducive to enhancing the willingness of remanufacturing firms to enter e-commerce platforms. Finally, we find that when the production quantity constraint of the remanufactured products is not binding, if the actual production cost of remanufactured products is high and consumers' satisfaction with offline remanufactured products is relatively low, information disclosure will benefit remanufacturing firms, however, when the production quantity constraint of the remanufactured products is binding, information disclosure has no impact on the remanufacturing firms' profits and operational decisions.

Mathematics Subject Classification. 90B50.

Received June 16, 2021. Accepted March 7, 2022.

1. Introduction

Nowadays, environmental issues such as global warming and the greenhouse effect caused by large amounts of carbon emissions have attracted widespread government attention. In this context, governments have formulated a series of regulations and policies to limit carbon emissions. For example, Finland implemented a carbon tax policy in 1990, and then Norway, Sweden, Denmark, the Netherlands, Germany, and other governments formulated corresponding carbon tax policies [4]. At the same time, China has put forward new requirements of low-carbon emission reduction for enterprises in the "Twelfth Five-Year Plan for Energy Conservation and

Keywords. Remanufacturing, e-commerce platform, channel choice, return service, logistics service.

[1] School of Tourism, Hainan University, Haikou 570228, P.R. China.
[2] School of Public Policy and Administration, Nanchang University, 999 Xuefu Avenue, Nanchang 330031, P.R. China.
[3] School of Tourism & Tourism Research Institute, Nanchang University, 999 Xuefu Avenue, Nanchang 330031, P.R. China.
*Corresponding author: 15779845652@163.com

Emission Reduction" [13]. With the society's increasing attention to resource utilization and environmental problems, remanufacturing firms are widely concerned because of their potential economic, environmental and social benefits. For example, Caterpillar has become one of the largest and most advanced remanufacturing firms in the world due to its 40 years of remanufacturing experience[1]. Aer, an automotive electronic remanufacturing firm, has cooperated with lots of car manufacturers to create a second chance to use for auto parts[2].

In addition, with the rapid development of e-commerce, consumers are increasingly inclined to shop online. E-commerce platforms such as Amazon.com, JD.com, and Taobao.com are emerging and gradually occupying a dominant market position. Amazon.com, as the world's largest e-commerce platform, provided more than 119 million products in 2019[3]. Taobao.com, as the largest e-commerce platform in China, has more than one billion products for sale, and its sales reached US $170 billion in 2012, far exceeding the total sales of Amazon and eBay in the same year[4]. At the same time, these e-commerce platforms also allow some third-party sellers to open third-party stores on these platforms. For example, the sales of third-party sellers on Amazon platform increased from 3% of the total sales to 58% in 2018[5]; as of 2016, more than 120 000 third-party sellers have entered JD.com[6]. Therefore, more and more manufacturing firms or brands choose to enter the e-commerce platforms. For example, brands such as Burberry in 2014 and MCM in 2018 chose to settle on Tmall.com to sell products [3].

Considering the vigorous development of the remanufacturing industry under the carbon tax policy and the market dominance of the e-commerce platform, whether remanufacturing firms should enter the e-commerce platform has become an urgent issue to be solved. In reality, some of the remanufacturing firms, such as MABBCO, as one of the oldest engine remanufacturing firms, has sold products on ebay.com[7]. Cardone, a well-known manufacturer of remanufactured car or truck replacement parts, has entered the Amazon.com[8]. While some of the remanufacturing firms choose not to enter the platform. For example, Davies Office, an office furniture remanufacturer in US, does not enter the platforms and has sold the remanufactured furniture *via* offline stores[9]. Besides, offering return services is also a common practice for firms to attract consumers in our daily life [1]. However, some data shows that in 2021 the offline return rate was about 8.89%, while the online return rate jumped to 30%[10]. It means that when remanufacturing firms decide whether to open online channels through entering the platforms, it is necessary for them to consider the impacts of return services. Therefore, if the remanufacturing firms choose to enter the platform, they can not only avoid huge cost of operating their own website but also attract more consumers brought by the platform. However, they need to bear the fee charged by the platform, and also need to undertake the return cost caused by a higher online return rate. If the remanufacturing firms choose not to enter the platform and only sell their remanufactured products through offline stores, they can avoid risks caused by opening a new channel and the higher online return rate, but they may be eliminated by the competitive market. It is a two-edge sword for the remanufacturing firms to enter the platforms. Thus, this paper aims to address the following question: How should the remanufacturing firms make optimal channel selection strategy when considering that these firms provide return services?

Moreover, there exists information asymmetry between the firms and the e-commerce platforms if the firms choose to enter the platform [27]. For instance, the production cost information of the remanufactured product is the private information owned by remanufactured firms and not easily obtained by the platforms [3], and this private information will cause huge impacts on the supply chain performances and product development [19].

[1] https://www.cat.com/en_US/ products/new/parts/reman.html.

[2] https://aertech.com/about/.

[3] https://www.scrapehero.com/many-products-amazon-sell-April-2019/.

[4] http://www.economist.com/news/briefing/21573980-alibaba-trailblazing-chinese-internet-giant-will-soon-go-public-worlds-greatest-bazaar.

[5] https://s2.q4cdn.com/299287126/files/doc_financials/annual/2018-Annual-Report.pdf.

[6] http://ir.jd.com/static-files/d4d1ee39-164d-4adb-9805-39f105d91eae.

[7] http://www.ebaystores.com/MABBCO-Enterprises.

[8] https://www.amazon.com/stores/A1+Cardone/page/4F31FB6A-637A-44AC-ACB8-BE5998CF3E26?ref_=ast_bln.

[9] https://www.daviesoffice.com.

[10] https://www.invespcro.com/blog/ecommerce-product-return-rate-statistics/.

However, due to the channel conflict between the online channel and offline channel, the remanufacturing firms are not always willing to share the private production cost information with the platforms [8]. Correspondingly, private production cost information will inevitably affect the operational strategies of the remanufacturing firms and platforms. Therefore, this paper also concentrates on the production cost information asymmetry issue and aims to answer the following question: How does the information asymmetry affect the channel selection strategy of the firms?

To explore the above issues, we construct the theoretical models considering consumer returns and online logistics. According to whether a remanufacturing firm enters the e-commerce platform and whether the production cost information is shared between the firm and the platform, we build the following three models: (a) the remanufacturing firm chooses not to enter the e-commerce platform (Model NP); (b) the remanufacturing firm chooses to enter the e-commerce platform and the production cost information is symmetry between the firm and the platform (Model YP); (c) the remanufacturing firm chooses to enter the e-commerce platform while the production cost information is asymmetry between the firm and the platform (Model YA). By optimizing these theoretical models, we have analyzed the optimal channel selection strategy of whether entering the e-commerce platform for remanufacturing firms, then, we also have presented some corresponding management suggestions based on optimal solutions of this paper for remanufacturing firms. These suggestions may serve as a guideline for the remanufacturing firms which are faced with the challenges of whether entering the platforms. Besides, this paper also focuses on the impacts of production cost information sharing and return services on the remanufacturing firms' channel selection strategies, which are not explored in the previous literature.

The organization of this paper is as follows. Section 2 makes a brief overview of the literature related to this paper. Models and demand functions are built in Section 3. Section 4 presents the main analysis results in the case of information asymmetry and information symmetry. In Section 5, this paper considers the production quantity constraint of the remanufactured products and its impacts on the remanufacturing firm's operation strategies. Conclusions and limitations are shown in Section 6. All the proofs are presented in the Appendix A.

2. Literature review

Our paper mainly studies the channel selection strategy of whether remanufacturing firms should enter the e-commerce platforms when considering asymmetric information. Therefore, we make a brief overview of the literature related to this paper.

Environmental issues such as global warming have caused a large number of troubles in people's daily life, thus, many scholars have focused on the development of the remanufacturing industry. For example, from the perspective of revenue management, Mitra [34] explores the revenue management strategy for remanufactured products by establishing a pricing model. Besides, Ovchinnikov [38] formulates the optimal pricing and remanufacturing strategy based on cost and revenue management. Liu *et al.* [29] work out the optimal production and pricing strategy for the monopoly manufacturers engaged in remanufacturing by solving the convex programming model. Sharma *et al.* [40] study the optimal reverse logistics inventory model when considering several remanufacturing batches. In addition, the remanufacturing strategy under the carbon tax policy has also been widely studied by scholars. For example, Liu *et al.* [28] research the impact of mandatory carbon emission requirements policies, *i.e.*, carbon tax policies and cap-and-trade policies, on the optimal decision-making of remanufacturing industries. Miao *et al.* [32] discuss the trade-in strategy for remanufactured products under the carbon tax and cap-and-trade policy. The results show that the implementation of carbon emission policies can reduce the demand for new products while promoting the sales of remanufactured products. Besides, Cao *et al.* [4] study the optimal trade-in strategy and warranty strategy for new products and remanufactured products under the carbon tax policy. The above papers have studied the remanufacturing firms' operation strategy from various aspects, but there is no literature on the channel selection strategy of whether to enter platform for remanufacturing firms. Therefore, we study this issue, and consider the channel selection strategy of remanufacturing firm in the case of asymmetric information and consumer returns, which is different from the above papers.

The research on channel selection has received extensive attention from scholars for a long time. For example, Coughlan [11] studies the channel selection strategy in the context of competition and cooperation, and the results show that selling products through intermediaries can enable firms to obtain more profits. With the advent of the e-commerce era, many scholars have begun to study the channel selection strategies between direct sales channels and traditional sales channels. For example, Chiang *et al.* [9] and Tsay and Agrawal [43] study whether firms should open up direct sales channels based on the original traditional sales channels. Lei *et al.* [24] discuss whether the direct channel should be carried out in the case of a manufacturer with multiple retailers. Yan *et al.* [47] investigate optimal channel choice of fresh agricultural supply chain, that is, whether the retailer should introduce the Internet channel. Khouja *et al.* [23] explore the channel selection problem of manufacturers after subdividing the consumer market. Subsequently, due to the prevalence of e-commerce platforms, some scholars also explore the channel selection strategy of whether to enter the e-commerce platforms. Shen *et al.* [41] construct two bargaining models between manufacturers and platforms, then study whether manufacturers should enter the e-commerce platform and how to cooperate with platform retailers and traditional distributors. Wang *et al.* [45] analyze the online channel selection strategy of manufacturers, that is, choosing direct sales channels or third-party e-commerce platform channels to expand their existing physical retail channels. Nowadays, O2O and omni-channel retail models are favored by various brands. Therefore, some scholars also conduct research on channel selection strategies under the new retail model. Niu *et al.* [37] explore the interaction of traffic congestion control, uniform pricing and the online-to-store channel, and find that uniform pricing can lead to a triple-win situation when the logistics cost is low. He *et al.* [16] study whether local B&M companies should adopt an O2O strategy. These papers study the optimal channel selection strategy of firms from many aspects, but they seldom consider whether firms should enter the e-commerce platform, except Shen *et al.* [41] and Wang *et al.* [45]. But different from them, our work not only considers the optimal platform entry strategy of remanufacturing firms but also considers that in the case of asymmetric information.

Information asymmetry has also caught many attentions from scholars around the world. The current literature about information asymmetry can mainly reviewed from two aspects, that is, product demand information asymmetry and production cost information asymmetry. For product demand information asymmetry, some papers study the information sharing strategy in the context of supply chain competition. For example, Ha *et al.* [14] explore the effects of demand information sharing strategy on the operation decisions when considering different competition models, *i.e.*, Cournot and Bertrand competition. Shang *et al.* [39] find out the optimal demand information sharing strategy of the retailer with two competing manufacturers. Besides, the impacts of demand information sharing strategy on the optimal channel structure have also been discussed by large amounts of scholars. Li *et al.* [25] and Huang *et al.* [18] explore the impact of retailers' demand information sharing strategy on the optimal encroachment decisions of manufacturers or suppliers. While Niu *et al.* [36] research the optimal manufacturer's channel structure between establishing a physical store and selling product *via* a local retailer when considering asymmetrical demand information. For asymmetrical production cost information, scholars have focused on the issue of contract design and coordination mechanism. Mukhopadhyay *et al.* [35] investigate the coordination problem between manufacturers and retailers in the case of asymmetric information of product value-added cost. Corbett *et al.* [10] explore the optimal purchase contract that the supplier should adopt under different asymmetric cost information structure. The above literature has made an extensive investigation on asymmetric information, while none of them has studied the optimal channel structure of whether entering the platforms to develop online channel for remanufacturing firms in the context of asymmetric production cost information, and this is the main contribution of this paper.

Moreover, considering that consumers have rights to return unsatisfied products in real life, therefore, firms need to consider the return service when formulating optimal production and pricing strategies. For example, Javadi *et al.* [20] research the optimal product pricing strategy considering return services in a dual-channel supply chain; Su [42] proposes a coordinated supply chain strategy based on return policies; Cao *et al.* [5] explore the dynamic cooperative advertising strategy when considering the return rate of goods. In addition, if a firm develops online channels to expand sales, it also needs to take online logistics delivery time into account. For example, Ulku and Bookbinder [44] study the optimal pricing and delivery time strategy when the third-party provides logistics services, and the research shows that the charging strategy based on the arrival time of order is not optimal for the third-party logistics providers. Min [33] discusses the optimal contract design about delivery time when the third-party logistics service provider determines the outsourcing logistics service. Unlike Ulku and Bookbinder [44], we mainly study the optimal platform entry strategy for remanufacturing firms considering asymmetric information, return services and the impacts of online logistics, which is the original contribution of our paper.

3. Theoretical models

3.1. Model descriptions and assumptions

Our paper mainly studies the channel selection strategy of whether remanufacturing firms should enter the e-commerce platform and whether the remanufacturing firms will disclose their private production cost information with platforms. Therefore, we assume that there is only one remanufacturing firm, an e-commerce platform and a third-party logistics service provider in the market, and the remanufacturing firm only sells one kind of remanufactured product. Remanufacturing firm has three kinds of channel selection strategies: (a) not entering the e-commerce platform (Model NP); (b) entering the e-commerce platform and sharing its private production cost information with the platform (Model YP); (c) entering the platform and not sharing the production cost information with the platform (Model YA).

Besides, in this paper, we assume that when the remanufacturing firm enters the platform, *i.e.*, in Models YP and YA, it should pay the referral fee f and an annual service fee T to the platform, where f is a decision variable and T is an exogenous variable [3, 21, 31]. This paper also assumes that when the remanufacturing firm enters the platform, the firm will adopt the third-party logistics and needs to pay a logistics fee k for the third-party logistics provider, where k is also a decision variable [6,17,26]. Although in practice, some platforms and logistics service providers will make fixed referral fees and logistics fees for the firms. However, we find that some platforms will change this referral fee in some cases. For instance, Flipkart, an e-commerce platform owned by Walmart, had divided the referral fee for the products with prices higher than and lower than Rs 300 into four slabs in 2019, where the platform previously provided the same rates for the products[11]. Besides, we also find that the third-party logistics providers will change the logistics fees in some cases, for instance, the logistics service providers will change their logistics fees every year on account of the rising fuel or labor costs[12]. Besides, USPS has announced the logistics fees they charged need to be adjusted in 2022[13]. Therefore, based on the above assumptions, this paper may give some suggestions for the platform and the third-party logistics service provider if they would like to reformulate or adjust the referral fee and logistics fee.

Since the carbon emissions of remanufactured products are lower than the new products' carbon emissions [28,32], therefore, we assume that the unit carbon emission of a new products is 1, and the unit carbon emission of a remanufactured product is b, where $b \in (0, 1)$ and b represents the carbon emission intensity of remanufactured products. Besides, under the carbon tax policy, the government will charge the remanufacturing firm for a carbon tax t on carbon emission per unit of the remanufactured product, which means the remanufacturing firm needs undertake the carbon tax bt for a remanufactured product it produced.

Moreover, we assume that there is competition between a new product and a remanufactured product in the original offline market. Similar to Zhang *et al.* [49] and He *et al.* [15], we assume that the retail price of new products is an exogenous variable. It is because that some firms adopt a fixed price strategy when releasing a new generation of products. For instance, when Huawei releases Mate 20 and Mate 30, respectively, its minimum

[11] https://www.businesstoday.in/latest/corporate/story/flipkart-cuts-commissions-shipping-fee-seller-numbers-rates-effective-june-24-e-commerce-company-207076-2019-06-11.

[12] https://mmotipsaz.com/how-to-prepare-for-shipping-rate-changes-in-2022/.

[13] https://www.shipstation.com/blog/usps-rate-increase-2022/.

TABLE 1. Notations.

Notation	Description
p_{ri}	Retail price of remanufactured products in offline ($i = s$) or online ($i = o$) channel
f	Referral fee
p_n	Retail price of new products
c_s	Operating costs of offline stores
h_s	Hassle cost
c_r	Production cost of remanufactured products
T	Annual service fee
b	Carbon emission intensity of remanufactured products
t	Carbon tax price per unit product
θ	Consumers' acceptance of remanufactured products
v	Consumers' willingness to pay for new products
α_{ri}	Consumer satisfaction with remanufactured products in offline ($i = s$) or online ($i = o$) channel
α_{ns}	Consumer satisfaction with new products in offline channel
s	Residual value of returned remanufactured products
t_l	Delivery time
λ	Consumers' sensitivity to delivery time
k	The logistics fee charged by the third-party logistics provider
c_T	The logistics cost undertaken by the third-party logistics provider
D	Demand function
$\prod$	Profit function

configuration release price is RMB 3999[14]; when Apple releases iPhone XS max and iPhone 11 Pro Max, the minimum configuration price is RMB 9599[15]. The main variables are shown in Table 1.

Note that, we utilize superscripts NP, YP and YA to represent Models NP, YP and YA.

3.2. Demand function

In Model NP, we assume that the consumers' satisfaction with the purchased remanufactured products or new products in the offline channel is α_{is} ($i = r$ or $i = n$) and the proportion of the consumers who are dissatisfied with the purchased products is $1 - \alpha_{is}$ [3, 7]. Since the quality of remanufactured product is lower than the quality of new product, thus, consumers' willingness to buy the remanufactured product is less than the willingness of buying the new product [20, 28]. Following Ferguson and Toktay [12] and Yan *et al.* [46], we assume that consumers' willingness to pay for new products v is subject to the uniform distribution of $[0, 1]$, and consumers' acceptance of purchasing remanufactured products is θ , which means that consumers' willingness to pay for remanufactured product is θv. In this case, the utility of consumers purchasing remanufactured products from offline channel is given as follows: $u_{rs}^{\rm NP} = \alpha_{rs}(\theta v - p_{rs}) + (1 - \alpha_{rs})(-h_s) - h_s$. The utility of consumers purchasing new products in the offline channel is given as follows: $u_{ns}^{\rm NP} = \alpha_{ns}(v - p_n) + (1 - \alpha_{ns})(-h_s) - h_s$, where h_s represents the hassle cost of purchasing products from offline channel. When $u_{rs}^{\rm NP} > 0$, $u_{rs}^{\rm NP} \geq u_{ns}^{\rm NP}$, consumers choose to buy remanufactured products from offline channel. At this time, consumers' demand is obtained as follows:

$$D_{rs}^{\rm NP} = \frac{(((p_n - h_s)\theta + h_s - p_{rs})\alpha_{ns} + 2h_s\theta)\alpha_{rs} - 2\alpha_{ns}h_s}{\alpha_{rs}\theta(\alpha_{ns} - \alpha_{rs}\theta)}. \tag{3.1}$$

[14] https://club.huawei.com/thread-21414035-1-1.html & https://club.huawei.com/thread-21414347-1-1.html.
[15] https://www.apple.com.cn/iphone/compare/.

When $u_{ns}^{\mathrm{NP}} > 0$, $u_{ns}^{\mathrm{NP}} > u_{rs}^{\mathrm{NP}}$, consumers choose to buy new products from offline channel, and the demand function is shown as follows:

$$D_{ns}^{\mathrm{NP}} = 1 - \frac{\alpha_{ns}(p_n - h_s) - \alpha_{rs}(p_{rs} - h_s)}{\alpha_{ns} - \alpha_{rs}\theta}. \tag{3.2}$$

In Model YP, we assume that consumers' satisfaction with remanufactured products from offline channel or online channel is α_{ri} ($i = s$ or $i = o$), and their satisfaction with new products from offline channel is α_{ns}. Since new product has a higher quality than remanufactured product and online return rate is higher than offline return rate, it is easy to obtain that $\alpha_{ns} > \alpha_{rs} > \alpha_{ro}$. Moreover, we assume that there is a type of consumers in the market who only choose to buy products in the offline channel and the proportion of this type of consumers is ρ, thus, the proportion of consumers without channel preference is $1-\rho$. Therefore, for such consumers having channel preferences, the consumer utility of purchasing remanufactured products in the offline channel is given as follows: $u_{rs}^{\mathrm{YP}} = \alpha_{rs}(\theta v - p_{rs}) + (1-\alpha_{rs})(-h_s) - h_s$. The utility of these consumers buying new products from offline channel is obtained as follows: $u_{ns}^{\mathrm{YP}} = \alpha_{ns}(v - p_n) + (1-\alpha_{ns})(-h_s) - h_s$. When $u_{rs}^{\mathrm{YP}} > 0$ and $u_{rs}^{\mathrm{YP}} \geq u_{ns}^{\mathrm{YP}}$, consumers with channel preferences will buy remanufactured products from offline channel. The demand function is given as follows:

$$D_{srs}^{\mathrm{YP}} = \frac{\rho((((p_n - h_s)\theta + h_s - p_{rs})\alpha_{ns} + 2h_s\theta)\alpha_{rs} - 2\alpha_{ns}h_s)}{(\alpha_{ns} - \alpha_{rs}\theta)\theta\alpha_{rs}}. \tag{3.3}$$

When $u_{ns}^{\mathrm{YP}} > 0$ and $u_{rs}^{\mathrm{YP}} < u_{ns}^{\mathrm{YP}}$, consumers with channel preferences will buy new products from offline channel. The demand function is shown as follows:

$$D_{sns}^{\mathrm{YP}} = \rho\left(1 - \frac{\alpha_{ns}(p_n - h_s) - \alpha_{rs}(p_{rs} - h_s)}{\alpha_{ns} - \alpha_{rs}\theta}\right). \tag{3.4}$$

Then, we focus on the consumers without channel preference. In Model YP, the consumer utility of buying new products from offline channel is shown as follow: $u_{ns}^{\mathrm{YP}} = \alpha_{ns}(v - p_n) + (1-\alpha_{ns})(-h_s) - h_s$. The consumer utility of purchasing remanufactured products in the offline channel is obtained as follow: $u_{rs}^{\mathrm{YP}} = \alpha_{rs}(\theta v - p_{rs}) + (1-\alpha_{rs})(-h_s) - h_s$. When the remanufacturing firm enters the e-commerce platform, we assume that consumers' online purchase intentions are affected by the delivery time [48]. Therefore, the consumer utility of buying remanufactured products in the online channel is shown as follows: $u_{ro}^{\mathrm{YP}} = \alpha_{ro}(\theta v - p_{ro}) - \lambda t_l$, where t_l represents the delivery time and λ represents consumers' sensitivity to delivery time. When $u_{rs}^{\mathrm{YP}} > 0$, $u_{rs}^{\mathrm{YP}} \geq u_{ro}^{\mathrm{YP}}$, $u_{rs}^{\mathrm{YP}} \geq u_{ns}^{\mathrm{YP}}$, the consumers will choose to purchase remanufactured products from offline channel, the demand function is obtained as follows:

$$D_{nrs}^{\mathrm{YP}} = (1-\rho)\left(\frac{\alpha_{ns}(p_n - h_s) - \alpha_{rs}(p_{rs} - h_s)}{\alpha_{ns} - \alpha_{rs}\theta} - \frac{\alpha_{rs}(p_{rs} - h_s) - \alpha_{ro}p_{ro} + 2h_s - \lambda t_l}{\theta(\alpha_{rs} - \alpha_{ro})}\right). \tag{3.5}$$

When $u_{ro}^{\mathrm{YP}} > 0$, $u_{ro}^{\mathrm{YP}} \geq u_{ns}^{\mathrm{YP}}$, $u_{ro}^{\mathrm{YP}} \geq u_{rs}^{\mathrm{YP}}$, consumers without channel preference will choose to buy remanufactured products from online channel, the demand function is given as follows:

$$D_{nro}^{\mathrm{YP}} = (1-\rho)\left(\frac{\alpha_{rs}(p_{rs} - h_s) - \alpha_{ro}p_{ro} + 2h_s - \lambda t_l}{\theta(\alpha_{rs} - \alpha_{ro})} - \frac{\alpha_{ro}p_{ro} + \lambda t_l}{\alpha_{ro}\theta}\right). \tag{3.6}$$

When $u_{ns}^{\mathrm{YP}} > 0$, $u_{ns}^{\mathrm{YP}} \geq u_{rs}^{\mathrm{YP}}$, $u_{ns}^{\mathrm{YP}} \geq u_{ro}^{\mathrm{YP}}$, these consumers will choose to buy new products from offline channel, the demand function is shown as follows:

$$D_{nns}^{\mathrm{YP}} = (1-\rho)\left(1 - \frac{\alpha_{ns}(p_n - h_s) - \alpha_{rs}(p_{rs} - h_s)}{\alpha_{ns} - \alpha_{rs}\theta}\right). \tag{3.7}$$

4. Analysis

In this section, we investigate the optimal channel selection strategy of the remanufacturing firm and the impacts of production cost information asymmetry on the firm's operation decisions through building three Models, *i.e.*, NP, YP and YA.

TABLE 2. Notations.

Model	Optimal decisions
NP	$p_{rs}^{\mathrm{NP}^*} = \frac{(((1-\theta)h_s+\theta p_n+s)\alpha_{rs}+bt-s+c_r+c_s-2h_s)\alpha_{ns}+2h_s\alpha_{rs}\theta}{2\alpha_{rs}\alpha_{ns}}$
YP	$f^{\mathrm{YP}^*} = \frac{(bt-\alpha_{rs}h_s+c_r+c_s+2h_s-s)\alpha_{ro}-\alpha_{rs}(bt+\lambda t_l+c_T+c_r-s)}{3\alpha_{rs}\alpha_{ro}}$
	$k^{\mathrm{YP}^*} = \frac{\alpha_{ro}(bt+c_r+c_s+2h_s-s)+\alpha_{rs}(-bt-h_s\alpha_{ro}-\lambda t_l+2c_T-c_r+s)}{3\alpha_{rs}}$
	$p_{rs}^{\mathrm{YP}^*} = \frac{(((1-\theta)h_s+\theta p_n+s)\alpha_{rs}+bt-s+c_r+c_s-2h_s)\alpha_{ns}+2h_s\alpha_{rs}\theta}{2\alpha_{ns}\alpha_{rs}}$
	$p_{ro}^{\mathrm{YP}^*} = \frac{\theta h_s}{\alpha_{ns}} + \frac{3\theta p_n+3s-(3\theta-2)h_s}{6} + \frac{2bt-2s+2c_r+2c_s+4h_s}{6\alpha_{rs}} + \frac{(bt-5\lambda t_l+c_T+c_r-s)}{6\alpha_{ro}}$
YA	$f^{\mathrm{YA}^*} = \frac{(bt-\alpha_{rs}h_s+c_e+c_s+2h_s-s)\alpha_{ro}-\alpha_{rs}(bt+\lambda t_l+c_T+c_e-s)}{3\alpha_{rs}\alpha_{ro}}$
	$k^{\mathrm{YA}^*} = \frac{\alpha_{ro}(bt+c_e+c_s+2h_s-s)+\alpha_{rs}(-bt-h_s\alpha_{ro}-\lambda t_l+2c_T-c_e+s)}{3\alpha_{rs}}$
	$p_{rs}^{\mathrm{YA}^*} = \frac{(((1-\theta)h_s+\theta p_n+s)\alpha_{rs}+bt-s+c_r+c_s-2h_s)\alpha_{ns}+2h_s\alpha_{rs}\theta}{2\alpha_{ns}\alpha_{rs}}$
	$p_{ro}^{\mathrm{YA}^*} = \frac{\theta h_s}{\alpha_{ns}} + \frac{3\theta p_n+3s-(3\theta-2)h_s}{6} + \frac{2bt-2s+2c_r+2c_s+4h_s}{6\alpha_{rs}} + \frac{(bt-5\lambda t_l+c_T+3c_r-2c_e-s)}{6\alpha_{ro}}$

4.1. Information symmetry

Firstly, we consider the case of without information asymmetry. Therefore, Models NP and YP should be analyzed in this section.

In Model NP, the remanufacturing firm does not enter the platform, and there is only the offline channel. Thus, the profit function of the remanufacturing firm is obtained as follows:

$$\prod_F^{\mathrm{NP}} = D_{rs}^{\mathrm{NP}} \left(\alpha_{rs}\left(p_{rs}-c_r\right)+\left(1-\alpha_{rs}\right)\left(s-c_r\right)-c_s-bt\right). \tag{4.1}$$

Where $\alpha_{rs}\left(p_{rs}-c\right)$ means the sale revenue of remanufacturing firm when consumers are satisfied with the products, and $\left(1-\alpha_{rs}\right)\left(s-c_r\right)$ represents the return loss of remanufacturing firm when consumers are not satisfied with the products. Besides, c_s represents the operation cost of offline channel and bt represents the carbon emission cost undertaken by the remanufacturing firm under the carbon tax policy.

The optimal decisions are presented in Table 2.

In Model YP, the remanufacturing firm enters the platform, thus, there are both online channel and offline channel. Due to the leading role played by the platforms, *e.g.*, Amazon.com and Taobao.com, and the importance of logistics services, we assume that the platform and the third-party logistics provider have the same market power and act as leaders in this paper. The decision sequence is given as follows: the platform and the third-party logistics provider firstly decides the referral fee f and the logistics fee k, respectively. Then, the remanufacturing firm decides the retail prices of online p_{ro} and offline channels p_{rs}. The profit functions of the remanufacturing firm, the platform and the third-party logistics service provider are given as follows:

$$\begin{aligned}\prod_F^{\mathrm{YP}} &= \left(\alpha_{rs}\left(p_{rs}-c_r\right)+\left(1-\alpha_{rs}\right)\left(s-c_r\right)-c_s-bt\right)\left(D_{srs}^{\mathrm{YP}}+D_{nrs}^{\mathrm{YP}}\right)\\ &\quad+\left(\alpha_{ro}\left(p_{ro}-f-c_r\right)+\left(1-\alpha_{ro}\right)\left(s-c_r\right)-bt-k\right)\left(D_{nro}^{\mathrm{YP}}\right)-T\end{aligned} \tag{4.2}$$

$$\prod_P^{\mathrm{YP}} = \alpha_{ro} f D_{nro}^{\mathrm{YP}} + T \tag{4.3}$$

$$\prod_T^{\mathrm{YP}} = \left(k-c_T\right) D_{nro}^{\mathrm{YP}}. \tag{4.4}$$

Note that, $(\alpha_{rs}(p_{rs}-c_r)+(1-\alpha_{rs})(s-c_r)-c_s-bt)\left(D^{\mathrm{YP}}_{srs}+D^{\mathrm{YP}}_{nrs}\right)$ means the sale profit from offline channel and $\left(D^{\mathrm{YP}}_{nro}\right)\left(\alpha_{ro}(p_{ro}-f-c_r)+(1-\alpha_{ro})(s-c_r)-bt-k\right)$ means the sale profit from online channel and T means the annual service fee charged by the platform.

The Optimal decisions are obtained in Table 2.

Comparing the remanufacturing firm's optimal profits under Models NP and YP, we could propose the following Theorem 4.1.

Theorem 4.1. *Analyzing the remanufacturing firm's channel selection strategy, we have*

(a) *if $T \le \bar{T}^S$, we have $\prod_F^{\mathrm{NP}} \le \prod_F^{\mathrm{YP}}$;*
(b) *and if $T > \bar{T}^S$, we have $\prod_F^{\mathrm{NP}} > \prod_F^{\mathrm{YP}}$.*

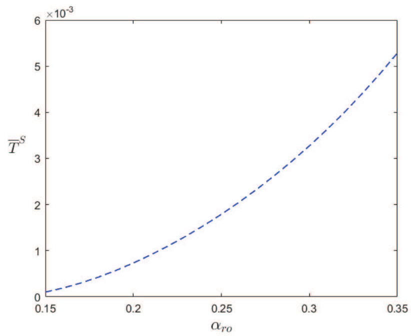
Theorem 4.1 shows that when the annual service fee charged by the platform is relatively small, the remanufacturing firm chooses to enter the e-commerce platform; otherwise, the remanufacturing firm chooses not to enter the platform. If the remanufacturing firm enters the e-commerce platform, the channel competition will intensify. Due to the opening of online sales channels, the sales of remanufactured products will increase. Therefore, when the annual service fee charged by the e-commerce platform is relatively small, it is more advantageous to enter the e-commerce platform. Otherwise, the remanufacturing enterprise may suffer losses if it chooses to enter the e-commerce platform.

Proposition 4.2. *The impact of consumer returns and online logistics on the remanufacturing firm's optimal platform entry strategy is given as follows:*

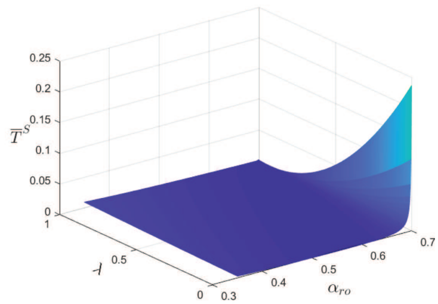
(a) *When $\alpha_{ro} \le \frac{\alpha_{rs}}{2}$, $\frac{\partial \bar{T}^S}{\partial \alpha_{ro}} \ge 0$;*
(b) *When $\frac{\alpha_{rs}}{2} < \alpha_{ro} < \alpha_{rs}$, if $\lambda \le \lambda_1$, $\frac{\partial \bar{T}^S}{\partial \alpha_{ro}} \ge 0$; otherwise, $\frac{\partial \bar{T}^S}{\partial \alpha_{ro}} < 0$.*

Proposition 4.2(a) and (b) show that when consumer's satisfaction with the remanufactured product purchased from the online channel is relatively small, as consumer's satisfaction with purchasing remanufactured products from online channel increases, the remanufacturing firm is more likely to enter the e-commerce platform. When consumers' satisfaction with remanufactured products purchased from online channel is relatively large, it will encourage the remanufacturing firm to enter the e-commerce platform only when consumer's sensitivity to the delivery time is below a certain threshold. Otherwise, it has a negative impact on the choice of the remanufacturing firm to enter the platform. This is because when the consumer's satisfaction with remanufactured product from online is relatively small, a small increase in consumer's satisfaction will bring about a huge improvement in firm's profit which will promote the possibility of the firm entering the platform. As the consumer's satisfaction with the remanufactured product from online channel increases, the margin profit brought by the increased satisfactions decreases. What's more, with the increase of the consumer's sensitivity of delivery time, the negative effect of a relatively long delivery time which affects consumer's willingness to purchase the remanufactured products from online channel plays an important role in the remanufacturing firm's decision of whether to enter the platform.

To better illustrate the impact of consumer returns and online logistics on the remanufacturing firm's optimal platform entry strategy, we present the following numerical analysis. And the main parameters settings are as follows: let $\alpha_{rs}=0.7$, $\rho=0.3$, $\theta=0.7$, $c_s=0.2$, $c_r=0.05$, $c_T=0.05$, $h_s=0.25$, $s=0.02$, $b=0.1$, $t=0.1$, $\lambda=0.1$, $t_l=0.1$, we could obtain Figure 1a. In addition, we set $\lambda\in(0,1)$, $\alpha_{ro}\in(0.35,0.7)$, $\alpha_{rs}=0.7$, $\rho=0.3$, $\theta=0.7$, $c_s=0.1$, $c_r=0.15$, $c_T=0.15$, $h_s=0.11$, $s=0.02$, $b=0.1$, $t=0.2$ and $t_l=0.1$, then we can get Figure 1b. Figure 1 shows that when consumers are less satisfied with remanufactured products purchased from online channel, as consumers' satisfaction with purchasing remanufactured products from online channel increases, the remanufacturing firm is more willing to enter the e-commerce platform. However, in the case of relatively high satisfaction with products purchased from online channel, only when consumers' sensitivity to delivery time is below a certain threshold, consumer's satisfaction with the remanufactured products purchased from online channel will have a positive impact on the decision-making of remanufacturing firm to enter the platform.



(a)



(b)

FIGURE 1. The impacts of consumer returns and online logistics. (a) When $\alpha_{ro} \leq \frac{\alpha_{rs}}{2}$. (b) When $\frac{\alpha_{rs}}{2} < \alpha_{ro} < \alpha_{rs}$.

Proposition 4.3. *The impact of carbon tax policy on the remanufacturing firm's optimal channel selection strategy is given as follows:* $\frac{\partial \bar{T}^S}{\partial t} < 0$.

Proposition 4.3 shows that under the carbon tax policy, as the carbon tax price set by the government increases, the willingness of the remanufacturing firm to enter the platform decreases. If the carbon tax price is greater, the cost of the remanufacturing firm will be greater. When the remanufacturing firm enters the e-commerce platform, it will increase the total demand of remanufactured products, but it also needs to pay more carbon taxes. Therefore, with the increase of the carbon tax price, the profit of the increased demand of remanufactured products brought by firm's online channel may be less than the cost borne by the carbon tax. At this time, the remanufacturing firm has less possibility of entering the e-commerce platform.

In short, the channel choice of the remanufacturing firm to enter the e-commerce platform needs to consider not only the annual service fee charged by the platform but also the carbon tax price set by the government.

Proposition 4.4. *Comparing the total carbon emissions under Models NP and YP, we have:* $E^{\mathrm{YP}^*} > E^{\mathrm{NP}^*}$.

Proposition 4.4 shows that when the remanufacturing firm enters the e-commerce platform, the total carbon emissions will be greater than the total carbon emissions when it does not enter the e-commerce platform. When the remanufacturing firm enters the e-commerce platform, although the demand of remanufactured products from the offline channel will decrease, the opening up of online channels increases consumers' desire to buy remanufactured products in the online channel, resulting in the rise of total demand for remanufactured products. As a result, the total carbon emissions will also rise, which will cause a certain amount of damage to the environment.

Proposition 4.5. *Comparing the optimal retail prices of remanufactured products and new products under Model NP and YP, we have:*

(a) $p_{rs}^{\mathrm{NP}^*} = p_{rs}^{\mathrm{YP}^*}$;
(b) *When* $\alpha_{ro} \leq \bar{\alpha}_{ro}$, $p_{ro}^{\mathrm{YP}^*} \leq p_{rs}^{\mathrm{YP}^*}$. *When* $\alpha_{ro} > \bar{\alpha}_{ro}$, *if* $\lambda \leq \lambda_2$, $p_{ro}^{\mathrm{YP}^*} \geq p_{rs}^{\mathrm{YP}^*}$; *otherwise,* $p_{ro}^{\mathrm{YP}^*} < p_{rs}^{\mathrm{YP}^*}$.

Proposition 4.5(a) indicates that the offline retail price of remanufactured products should remain unchanged whether the remanufacturing firm enters the e-commerce platform or not. When the remanufacturing firm enters the e-commerce platform, its online and offline channel will have a certain degree of competition. Since this competition is internal, the firm should keep the retail prices of its offline remanufactured products unchanged to maintain customers.

Proposition 4.5(b) indicates that when consumers' satisfaction with remanufactured products purchased from online channel is below a certain threshold, the online retail price of remanufacturing products will be lower than the offline retail price of remanufacturing products. When consumers' satisfaction with remanufactured products purchased from online channel is greater than the threshold, the online retail price of remanufacturing products will be higher than the offline retail price of remanufacturing products only if consumers' sensitivity to delivery time is less than a certain threshold. Otherwise, the online retail price of remanufacturing products will be lower than the offline retail price of remanufacturing products. When consumers' satisfaction with remanufactured products purchased from online channel is relatively low, the remanufacturing firm will lower the retail price to attract more consumers to buy remanufactured products from online channel. When consumers are more satisfied with remanufactured products purchased from online channel and less sensitive to delivery time, consumers will be more willing to buy remanufactured products from online channel. It enables the remanufacturing firm to set a higher online retail price. However, when consumers are very sensitive to the delivery time, consumers' willingness to buy remanufactured products from online channel will decrease, which will cause the remanufacturing firm to lower the retail prices to attract consumers.

In short, when the remanufacturing firm enters the e-commerce platform, it should maintain the offline retail price of remanufactured products, while the online retail price of remanufactured products should depend on consumers' satisfaction with remanufactured products purchased from online channel and consumers' sensitivity to delivery time.

Proposition 4.6. *The offline and total demands of remanufactured products under Models NP and YP are:*
(a) $D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}} < D_{rs}^{\mathrm{NP}}$;
(b) $D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}} + D_{nro}^{\mathrm{YP}} > D_{rs}^{\mathrm{NP}}$.

Proposition 4.6 indicates that when the remanufacturing firm enters the e-commerce platform, the offline demand of remanufactured products will decrease, but the total demand of remanufactured products will increase. It can be seen from Proposition 4.5 that when the remanufacturing firm enters the e-commerce platform, its offline retail prices have not changed. Due to the internal channel competition, the demand of offline sales channels is reduced. However, some new consumers begin to buy remanufactured products online due to the opening of online channels, which widens the market. Since the increased demand of online channels is greater than the reduced demand of offline sales channels, the total demand for remanufacturing firm has increased.

4.2. Information asymmetry

In Model YA, we assume that there is asymmetric production cost of remanufactured product information between e-commerce platforms and remanufacturing firms. And the production cost of remanufactured products can be divided into two cases: a low production cost (c_{rL}) and a high production cost (c_{rH}), and the probabilities are η and $1-\eta$ respectively in this paper. In the case of asymmetric production cost of remanufactured product information, the expected value of the production cost of the remanufactured products is $c_e = \eta c_{rL} + (1-\eta)\, c_{rH}$ [3].

In Model YA, since the platform and the third-party logistics provider act as leaders, and they do not know the actual production cost information of remanufactured product, they make the optimal decisions based on the expected production cost of remanufactured product. However, the remanufacturing firm know it private production cost, thus, it makes the optimal retail prices based on the actual production cost information and the decisions made by the platform and the third-party logistics provider. Therefore, in Model YA, the profit functions of the remanufacturing firm, the platform, and the third-party logistics provider are given as follows:

$$\prod_F^{\mathrm{YA}} = \left(\alpha_{rs}\left(p_{rs} - c_r\right) + \left(1 - \alpha_{rs}\right)\left(s - c_r\right) - c_s - bt\right)\left(D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}}\right) + \left(\alpha_{ro}\left(p_{ro} - f - c_r\right) + \left(1 - \alpha_{ro}\right)\left(s - c_r\right) - bt - k\right)\left(D_{nro}^{\mathrm{YP}}\right) - T \tag{4.5}$$

$$\prod_P^{\mathrm{YA}} = \eta \alpha_{ro} f D_{Lnro}^{\mathrm{YP}} + (1-\eta)\, \alpha_{ro} f D_{Hnro}^{\mathrm{YP}} + T \tag{4.6}$$

$$\prod_{T}^{\mathrm{YA}} = \eta\left(k - c_T\right) D_{Lnro}^{\mathrm{YP}} + (1-\eta)\left(k - c_T\right) D_{Hnro}^{\mathrm{YP}}. \tag{4.7}$$

Where D_{Lnro}^{YP} or D_{Hnro}^{YP} represents the demand function of online remanufactured product when the expected production cost of the remanufactured product is low or high.

The optimal decisions are presented in Table 2.

Comparing the remanufacturing firm's optimal profits between Models NP and YA, we could obtain the following Theorem 4.7.

Theorem 4.7. *In the case of asymmetric production cost information, the channel selection strategy for the remanufacturing firm is given as follows:*

(a) *if* $T \leq \bar{T}^A$*, we have* $\prod_F^{\mathrm{NP}} \leq \prod_F^{\mathrm{YA}}$*;*
(b) *and if* $T > \bar{T}^A$*, we have* $\prod_F^{\mathrm{NP}} > \prod_F^{\mathrm{YA}}$*.*

Theorem 4.7 shows that in the case of asymmetric production cost information, the channel selection strategy for the remanufacturing firm to enter the platform depends on the size of the annual service fee charged by the platform. When the annual service fee charged by the platform is less than a certain threshold, the remanufacturing firm will choose to enter the e-commerce platform; otherwise, the remanufacturing firm will not enter, which further verifies the conclusions of Theorem 4.1.

Proposition 4.8. *Comparing the thresholds of the annual service fee charged by platform under Models YP and YA, we have:*

(a) *When* $c_r = c_{rH}$*, if* $\alpha_{rs} \leq \bar{\alpha}_{rs}$*,* $\bar{T}^A \leq \bar{T}^S$*; otherwise,* $\bar{T}^A > \bar{T}^S$*;*
(b) *When* $c_r = c_{rL}$*,* $\bar{T}^A > \bar{T}^S$*.*

Proposition 4.8 shows that when the actual production cost of remanufactured products is high, the threshold of the annual service fee in the case of information symmetry is less (higher) than that in the case of information asymmetry only when consumers are more (less) satisfied with the products purchased from offline channel. When the actual production cost of remanufactured products is low, the threshold of the annual service fee in the case of information symmetry is lower than that in the case of information asymmetry. When the actual production cost of remanufactured products is high, the remanufacturing firm will set higher retail prices, the platform and the third-party logistics provider will charge higher referral fee and logistics fee in the case of asymmetric information. Besides, consumers' low satisfaction with remanufactured products from offline channel means that consumers will be more declined to purchase remanufactured products from offline channel or even choose not to buy remanufactured products. At this time, in the case of information asymmetry, the remanufacturing firm will obtain less profits and bear more referral fee and logistics fee, therefore, the willingness of remanufacturing firm to enter the platform is smaller than that of information symmetry. When consumer's satisfaction with remanufactured products from offline channel is relatively high, more consumers are willing to buy products from offline channel and the profits obtained from offline channel may be higher than the costs of referral and logistics fees from online channel. Therefore, the willingness of entering the platform in the case of information asymmetry is higher than that in the case of information symmetry. When the actual production cost of remanufactured products is low, the remanufacturing firm will set lower retail prices, and the platform and the third-party logistics provider will charge lower referral fee and logistics fee. At this time, the remanufacturing firm is more willing to enter the platform.

To better illustrate the remanufacturing firm's willingness to enter the platform under the case of symmetric information and asymmetric information, we have presented the following numerical analysis. Note that letter S represents information symmetry, letter A represents information asymmetry in Figure 2. And the relevant parameters are set as follows: $\theta = 0.7$, $\alpha_{ro} = 0.6$, $c_s = 0.2$, $c_T = 0.1$, $h_s = 0.2$, $s = 0.05$, $b = 0.5$, $t = 0.2$, $\lambda = 0.1$, $\rho = 0.3$, $t_l = 0.1$ and $\alpha_{rs} \in (0.65, 1)$. Let $c_r = 0.4$, we can get the Figure 2a. Let $c_r = 0.1$, we can get the Figure 2b. It can be seen from Figure 2 that only when c_r is high and α_{rs} is below a certain threshold, the

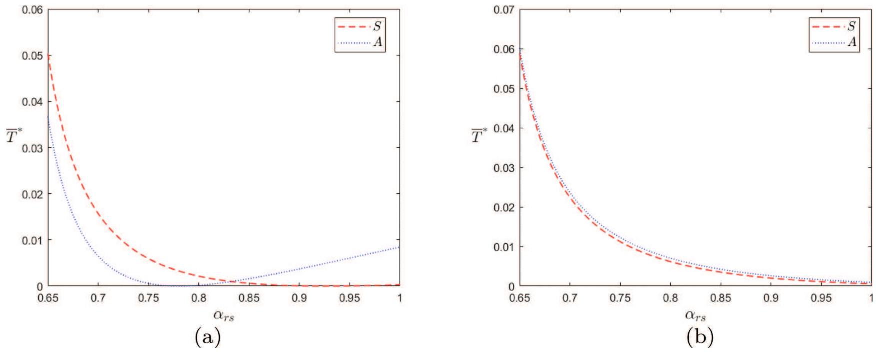


FIGURE 2. Remanufacturing firm's willingness to enter the platform. (a) $c_r = 0.4$. (b) $c_r = 0.1$.

threshold of annual service fee in the case of information asymmetry is less than that in the case of information symmetry, which means that the remanufacturing firm in the case of information symmetry is more willing to enter the platform. When the actual production cost of remanufactured products is relatively low, the threshold of annual service fee is greater than that in the case of information asymmetry, that is, the remanufacturing firm is more reluctant to enter the e-commerce platform in the case of information symmetry.

Proposition 4.9. *Comparing the profits of the remanufacturing firm under Models YP and YA, we have:*

(a) *When $c_r = c_{rH}$, if $\alpha_{rs} \leq \bar{\alpha}_{rs}$, $\prod_F^{\text{YP}} \geq \prod_F^{\text{YA}}$; otherwise, $\prod_F^{\text{YP}} < \prod_F^{\text{YA}}$;*
(b) *When $c_r = c_{rL}$, $\prod_F^{\text{YP}} < \prod_F^{\text{YA}}$.*

Proposition 4.9(a) shows that when $c_r = c_{rH}$, the profit of the remanufacturing firm with asymmetric information is less than the profit with symmetric information only when α_{rs} is less than a certain threshold; otherwise, the profit of the remanufacturing firm in the case of information symmetry is smaller. When the actual production cost of the remanufactured products is high, the platform and the third-party logistics provider will set higher referral fee and logistics fee, and the remanufacturing firm will set a higher online retail price. If consumer's satisfaction with the remanufactured products purchased from offline channel is relatively low, consumers may not buy remanufactured products from offline channel or even not purchase remanufactured products. At this time, in the case of asymmetric information, the remanufacturing firm will obtain less profits and also needs to bear higher costs, therefore, the remanufacturing firm will choose to disclose the production cost information with the platform. If consumer's satisfaction with the remanufactured products purchased from offline channel is relatively high, more consumers may choose to buy products from offline channel, at this time, the profits obtained from offline channel may be higher than the referral fee and logistics fee undertaken by the remanufacturing firm from online channel. Therefore, the remanufacturing firm may choose not to disclose the production cost information.

Proposition 4.9(b) demonstrates that when the actual production cost of the remanufactured products is low, the remanufacturing firm will not disclose the production cost information with the platform. When the actual production cost of the remanufactured products is low, the platform and the third-party logistics service provider in the case of asymmetric information will charge lower referral fee and logistics fee, thus, the remanufacturing firm is less willing to share the production cost information with the platform.

Proposition 4.9 implies that when the actual production cost of remanufactured products is high, if consumer's satisfaction with the remanufactured product purchased from offline channel is relatively low (high), non-disclosure of production cost information will harm (benefit) remanufacturing firms. However, when the actual production cost is relatively low, non-disclosure of production cost information will benefit remanufacturing firms.

Proposition 4.10. *Comparing the optimal solutions under Models YA and YP, we have:*

(a) $p_{rs}^{\mathrm{YA}^*} = p_{rs}^{\mathrm{YP}^*}$;
(b) *When* $c_r = c_{rH}$, $f^{\mathrm{YA}^*} \geq f^{\mathrm{YP}^*}$, $k^{\mathrm{YA}^*} \geq k^{\mathrm{YP}^*}$, $p_{ro}^{\mathrm{YA}^*} \geq p_{ro}^{\mathrm{YP}^*}$;
(c) *When* $c_r = c_{rL}$, $f^{\mathrm{YA}^*} < f^{\mathrm{YP}^*}$, $k^{\mathrm{YA}^*} < k^{\mathrm{YP}^*}$, $p_{ro}^{\mathrm{YA}^*} < p_{ro}^{\mathrm{YP}^*}$.

Proposition 4.10 shows that the optimal offline retail price of remanufactured products will not be affected by asymmetric information. When the actual production cost of remanufactured products is high, the platform and third-party logistics providers will charge higher referral fee and logistics fee, at this time, the remanufacturing firm will set a higher online retail price of remanufactured products. When the actual production cost of remanufactured products is low, the platform and the third-party logistics provider will also charge relatively lower referral fee and logistics fee in the case of asymmetric information. Besides, the optimal online retail price of remanufactured products will be lower than the online retail price under the case of symmetric information.

Proposition 4.10 implies that asymmetric information will not affect the optimal offline retail prices of remanufactured products. However, it will affect the optimal online retail prices of remanufactured products, the optimal referral fees charged by the platforms, and the optimal logistics fees charged by third-party logistics providers.

Proposition 4.11. *Analyzing the demands of remanufactured products under Models YA and YP, we have:*

(a) *When* $c_r = c_{rH}$, $D_{srs}^{\mathrm{YA}} + D_{nrs}^{\mathrm{YA}} \geq D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}}$;
(b) *When* $c_r = c_{rL}$, $D_{srs}^{\mathrm{YA}} + D_{nrs}^{\mathrm{YA}} < D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}}$;
(c) *When* $c_r = c_{rH}$, $D_{srs}^{\mathrm{YA}} + D_{nrs}^{\mathrm{YA}} + D_{nro}^{\mathrm{YA}} \leq D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}} + D_{nro}^{\mathrm{YP}}$;
(d) *When* $c_r = c_{rL}$, $D_{srs}^{\mathrm{YA}} + D_{nrs}^{\mathrm{YA}} + D_{nro}^{\mathrm{YA}} > D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}} + D_{nro}^{\mathrm{YP}}$.

Proposition 4.11(a) and (b) show that when the actual production cost of remanufactured products is high (low), the offline demand of remanufactured products under asymmetric information is larger (smaller) than that under symmetric information, while Proposition 4.11(c) and (d) show that when the actual production cost of remanufactured products is high (low), the total demand under asymmetric information is smaller (larger). It can be seen from Proposition 4.10 that when the actual production cost of remanufactured products is high, the remanufacturing firm will set a higher online retail price, while the offline retail price of remanufactured products remains unchanged, thus, consumers will choose to buy remanufactured products from offline stores or not to buy remanufactured products. At this time, offline demand of remanufactured products will increase, but the total demand of remanufactured products will decrease.

Proposition 4.12. *Comparing the total carbon emissions under Models YA and YP, we have:*

(a) *When* $c_r = c_{rH}$, $E^{\mathrm{YA}^*} \leq E^{\mathrm{YP}^*}$;
(b) *When* $c_r = c_{rL}$, $E^{\mathrm{YA}^*} > E^{\mathrm{YP}^*}$.

Proposition 4.12 shows that when the actual production cost of remanufactured products is high (low), the total carbon emissions in the case of asymmetric information is smaller (larger) than that in the case of symmetric information. It can be seen from Proposition 4.11 that when the actual production cost of remanufactured products is high, the total demand in the case of information symmetry is greater, that is, the total carbon emissions of the remanufacturing firm is greater, which will cause certain damage to the environment. Therefore, when the actual production cost of remanufactured products is high, non-disclosure of information may reduce the profit of the remanufacturing firm under certain conditions, but it will have a beneficial impact on the environment. When the actual production cost of remanufactured products is low, non-disclosure of information will increase the profit of the remanufacturing firm, but it will harm the environment.

5. Extension

In the base models, we have not considered the production quantity constraint of remanufactured products, therefore, in this section, we consider the case of two periods, where there are only new products in the first period and both new and remanufactured products in the second period [30]. The production quantity of remanufactured products in the second period is constrained by the production quantity of new products in the first period. Since there are only new products in the first period, thus, the consumer utility is: $u_{ns}^1 = \alpha_{ns}(v - p_n) + (1 - \alpha_{ns})(-h_s) - h_s$. Therefore, it is easy to obtain that the production quantity of new product in the first period is $D_{ns}^1 = 1 - (\alpha_{ns}(p_n - h_s) + 2h_s)/\alpha_{ns}$; in the second period, there are remanufactured products and new products, and the remanufacturing firm will decide whether to enter the platform and share its private production cost information with the platform. Thus, there are three strategies for the remanufacturing firm in the second period, which are similar to the base models, and we use superscript E to represent the extended models of the second period.

5.1. Model NPE

In model NPE, the remanufactured firm does not enter the platform in the second period. Similar to the base models, the profit function of the platform is given as follows, where the demand functions in the second period are the same as the base models:

$$\prod_F^{\mathrm{NPE}} = D_{rs}^{\mathrm{NP}}\left(\alpha_{rs}(p_{rs} - c_r) + (1 - \alpha_{rs})(s - c_r) - c_s - bt\right) \tag{5.1}$$
$$\text{s.t.} \quad 0 < D_{rs}^{\mathrm{NP}} \le D_{ns}^1.$$

There are two cases satisfy the positive product demands and profits, that is, (a) the quantity constraint of remanufactured products is not binding ($D_{rs}^{\mathrm{NP}} < D_{ns}^1$); (b) the quantity constraint of remanufactured products is binding ($D_{rs}^{\mathrm{NP}} = D_{ns}^1$). Since in the case of $D_{rs}^{\mathrm{NP}} < D_{ns}^1$, the optimal decisions, profits and channel selection strategies of the remanufacturing firm are the same as the base models, we omit it and only analyze the firm's optimal operational strategy in the case of $D_{rs}^{\mathrm{NP}} = D_{ns}^1$. Optimal decisions in the case of $D_{rs}^{\mathrm{NP}} = D_{ns}^1$ under Model NPE are shown in the Appendix A.

5.2. Model YPE

In Model YPE, the remanufacturing firm enters the platform with symmetrical information. Hence, the profit functions of the remanufacturing firm, the platform and the third-party logistics provider are given as follows:

$$\begin{aligned}\prod_F^{\mathrm{YPE}} &= \left(\alpha_{rs}(p_{rs} - c_r) + (1 - \alpha_{rs})(s - c_r) - c_s - bt\right)\left(D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}}\right) \\ &\quad + \left(\alpha_{ro}(p_{ro} - f - c_r) + (1 - \alpha_{ro})(s - c_r) - bt - k\right) D_{nro}^{\mathrm{YP}} - T\end{aligned} \tag{5.2}$$

$$\prod_P^{\mathrm{YPE}} = \alpha_{ro} f D_{nro}^{\mathrm{YP}} + T \tag{5.3}$$

$$\prod_T^{\mathrm{YPE}} = (k - c_T) D_{nro}^{\mathrm{YP}} \tag{5.4}$$
$$\text{s.t.} \quad 0 < D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}} + D_{nro}^{\mathrm{YP}} \le D_{ns}^1.$$

Similar to Model NPE, the optimal decisions in the case of $D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}} + D_{nro}^{\mathrm{YP}} = D_{ns}^1$ under Model NPE are presented in the Appendix A.

5.3. Model YAE

In Model YAE, the remanufacturing firm enters the platform with asymmetrical information. The profit functions of the remanufacturing firm, the platform and the third-party logistics provider are shown as follows:

$$\prod_F^{\text{YAE}} = (\alpha_{rs}(p_{rs} - c_r) + (1 - \alpha_{rs})(s - c_r) - c_s - bt)\left(D_{srs}^{\text{YP}} + D_{nrs}^{\text{YP}}\right) + (\alpha_{ro}(p_{ro} - f - c_r) + (1 - \alpha_{ro})(s - c_r) - bt - k)\left(D_{nro}^{\text{YP}}\right) - T \tag{5.5}$$

$$\prod_P^{\text{YAE}} = \eta\alpha_{ro} f D_{Lnro}^{\text{YP}} + (1 - \eta)\,\alpha_{ro} f D_{Hnro}^{\text{YP}} + T \tag{5.6}$$

$$\prod_T^{\text{YAE}} = \eta\,(k - c_T)\,D_{Lnro}^{\text{YP}} + (1 - \eta)\,(k - c_T)\,D_{Hnro}^{\text{YP}} \tag{5.7}$$

$$\text{s.t.}\quad 0 < D_{srs}^{\text{YP}} + D_{nrs}^{\text{YP}} + D_{nro}^{\text{YP}} \le D_{ns}^{1}.$$

The optimal decisions in the case of $D_{srs}^{\text{YP}}+D_{nrs}^{\text{YP}}+D_{nro}^{\text{YP}} = D_{ns}^{1}$ under Model YAE are shown in the Appendix A.

Remark 5.1. When the production quantity of the remanufactured products is binding, comparing the optimal remanufacturing firm's profits under Model NPE and YPE, we have:

(a) if $T \le \bar{T}^{\text{SE}}$, we have $\prod_F^{\text{NPE}} \le \prod_F^{\text{YPE}}$;
(b) and if $T > \bar{T}^{\text{SE}}$, we have $\prod_F^{\text{NPE}} > \prod_F^{\text{YPE}}$.

The conclusion of Remark 5.1 is similar to Theorem 4.1, that is, when the production quantity constraint of remanufactured product is binding, if the annual service fee is relatively low, the remanufacturing firm will enter the platform; otherwise, it will not. This result implies that the firm's willingness to enter the platform relies on the size of annual service fee charged by the platform.

Remark 5.2. When the production quantity of the remanufactured products is binding, comparing the optimal remanufacturing firm's profits under Model NPE and YAE, we have:

(a) if $T \le \bar{T}^{\text{AE}}$, we have $\prod_F^{\text{NPE}} \le \prod_F^{\text{YAE}}$;
(b) and if $T > \bar{T}^{\text{AE}}$, we have $\prod_F^{\text{NPE}} > \prod_F^{\text{YAE}}$.

Resembles to Theorem 4.7, when considering the production constraint of remanufactured products, the annual service fee charged by the platform will influence the channel selection strategy of the remanufacturing firm, which further verify the robustness of the main conclusion in this paper.

Similar to the based models, when the production quantity constraint of remanufactured products is binding, to explore the impacts of production cost information sharing on the remanufacturing firm's optimal channel choice, we propose the following Corollary.

Corollary 5.3. *Comparing the size relationships between $\bar{T}^{\text{SE}}$ and $\bar{T}^{\text{AE}}$, we have $\bar{T}^{\text{SE}} = \bar{T}^{\text{AE}}$.*

Corollary 5.3 implies that when the production quantity constraint of the remanufacturing is binding, the production cost information sharing strategy has no impact on the remanufacturing firm's optimal channel selection strategy. When the production quantity constraint of the remanufactured product is binding, that is, the production quantity of the remanufactured products in the second period is equivalent to the production quantity of the new products in the first period, at this time, the production cost of the remanufactured product is relatively low and the optimal retail prices of the remanufacturing firm are little affected by the production cost of the remanufactured product. Therefore, in this context, the asymmetrical production cost information of the remanufactured product will not affect the firm's channel selection strategy.

6. Conclusions

This paper studies the channel selection strategy for remanufacturing firms when considering asymmetric production cost information and return service. According to the channel choice of the remanufacturing firm, our work considers the following three strategies: (a) the remanufacturing firm chooses not to enter the e-commerce platform; (b) the remanufacturing firm chooses to enter the e-commerce platform and the production cost information is symmetry between the firm and the platform; (c) the remanufacturing firm chooses to enter the e-commerce platform while the production cost information is asymmetry between the firm and the platform. Through the above analysis, we draw the following main conclusions:

In the case of information symmetry, when the annual service fee charged by e-commerce platforms is relatively small, remanufacturing firms should enter the platforms; otherwise, they should not enter the platforms. Besides, when consumer's satisfaction with the remanufactured product purchased from online channel is relatively small, remanufacturing firms are more inclined to enter the e-commerce platforms with the increase of consumers' satisfaction with the remanufactured products purchased from online channel. If consumer's satisfaction is relatively large, only when the sensitivity of consumers to the delivery time is below a certain threshold, the remanufacturing firms will be more willing to enter the platforms with the increase of consumers' satisfaction with the remanufactured products purchased from online channel; otherwise, it has a negative effect on the remanufacturing firms' willingness to enter the platforms. Besides, considering the carbon tax policy, as the carbon tax price set by the government increases, remanufacturing firms are less likely to enter platforms.

In the case of information asymmetry, the channel selection strategy for remanufacturing firms depends on not only the annual service fee charged by platforms but also the production cost of the remanufactured product estimated by platforms. When the actual production cost of remanufactured products is relatively low, the remanufacturing firms are more willing to enter the platforms. When the actual production cost of remanufactured products is relatively high and consumer's satisfaction with the remanufactured products purchased from offline channel is relatively low, the remanufacturing firms are less willing to enter the platforms. What's more, without binding on production quantity constraint of remanufactured products, when the actual production cost of remanufactured products is high, if consumer's satisfaction with the remanufactured product purchased from offline channel is relatively small, non-disclosure of information will harm remanufacturing firms, but will bring a favorable impact on the environment. However, when the actual production cost is low, non-disclosure of information will benefit remanufacturing firms but harm the environment. When the production quantity constraint of remanufactured products is binding, information disclosure has no impact on the remanufacturing firms' profits and operational decisions.

There are also many limitations in this paper. First of all, we only consider the channel selection strategy of a remanufacturing firm. In practice, there will be multiple remanufacturing firms competing in the markets. Secondly, we assume the price of the new product is exogenous, perhaps using it as a decision variable will have different results. Finally, we only consider one e-commerce platform in our model. In the future research, we can study the channel selection strategy for the remanufacturing firms facing competition from multiple platforms.

Appendix A. Proof

A.1. Proof of Theorem 4.1

Proof. In Model NP, the profit function of the remanufacturing firm is: $\prod_F^{\mathrm{NP}} = D_{rs}^{\mathrm{NP}} (\alpha_{rs} p_{rs} + (1-\alpha_{rs}) s - c_s - c_r - bt)$ since $\frac{\partial \prod_F^{\mathrm{NP}\,2}}{\partial {p_{rs}}^2} = -\frac{2\alpha_{ns}\alpha_{rs}}{(\alpha_{ns}-\alpha_{rs}\theta)\theta} < 0$ is a concave function, there is a maximum value. Let $\frac{\partial \prod_F^{\mathrm{NP}}}{\partial p_{rs}} = 0$, we can get $p_{rs}^{\mathrm{NP}^*} = \frac{(((1-\theta)h_s+\theta p_n+s)\alpha_{rs}+bt-s+c_r+c_s-2h_s)\alpha_{ns}+2h_s\alpha_{rs}\theta}{2\alpha_{rs}\alpha_{ns}}$.

In Model YP, the profit functions of the e-commerce platform, the third-party logistics provider, and the remanufacturing firm are: $\prod_F^{\mathrm{YP}} = \left(\alpha_{rs} p_{rs} + (1-\alpha_{rs}) s - c_r - c_s - bt\right) \left(D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}}\right) + (\alpha_{ro}(p_{ro}-f) + (1-\alpha_{ro}) s - c_r - bt - k) \left(D_{nro}^{\mathrm{YP}}\right) - T$, $\prod_P^{\mathrm{YP}} = \alpha_{ro} f D_{nro}^{\mathrm{YP}} + T$, $\prod_T^{\mathrm{YP}} = (k - c_T) D_{nro}^{\mathrm{YP}}$. The Hessian matrix of the profit function of the remanufacturing firm is:

$$H\left(\prod_{F}^{\text{YP}}\right)=\begin{bmatrix}\frac{\partial\prod_{F}^{\text{YP}2}}{\partial p_{ro}{}^{2}} & \frac{\partial\prod_{F}^{\text{YP}2}}{\partial p_{ro}\partial p_{rs}}\\ \frac{\partial\prod_{F}^{\text{YP}2}}{\partial p_{rs}\partial p_{ro}} & \frac{\partial\prod_{F}^{\text{YP}2}}{\partial p_{rs}{}^{2}}\end{bmatrix}$$
$$=\begin{bmatrix}-\frac{2\alpha_{ro}\alpha_{rs}(1-\rho)}{(\alpha_{rs}-\alpha_{ro})\theta} & \frac{2\alpha_{ro}\alpha_{rs}(1-\rho)}{\theta(\alpha_{rs}-\alpha_{ro})}\\ \frac{2\alpha_{ro}\alpha_{rs}(1-\rho)}{\theta(\alpha_{rs}-\alpha_{ro})} & \frac{2\alpha_{rs}((\theta_{o}(-1+\rho)\alpha_{ro}+\alpha_{ns})\alpha_{rs}-\alpha\alpha_{ns}\alpha_{ro})}{(\alpha_{ns}-\theta\alpha_{rs})(\alpha_{ro}-\alpha_{rs})\theta}\end{bmatrix}.$$

It is a negative definite matrix with a maximum value. Therefore, by seeking a partial derivative of the retail price, we can obtain: $p_{rs}^{\text{YP}}=\frac{(((1-\theta)h_s+\theta p_n+s)\alpha_{rs}+bt-s+c_r+c_s-2h_s)\alpha_{ns}+2h_s\alpha_{rs}\theta}{2\alpha_{ns}\alpha_{rs}}$, $p_{ro}^{\text{YP}}=\frac{(((p_n-h_s)\theta+f+s)\alpha_{ro}+bt-\lambda t_l+k-s+c_r)\alpha_{ns}+2\theta\alpha_{ro}h_s}{2\alpha_{ns}\alpha_{ro}}$.

Substitute the initial decision of the retail price into the profit function of the platform and the third-party logistics provider, let $\frac{\partial\prod_{P}^{\text{YP}}}{\partial f}=0$, and $\frac{\partial\prod_{T}^{\text{YP}}}{\partial k}=0$, we can get $f^{\text{YP}^*}=\frac{(bt-\alpha_{rs}h_s+c_r+c_s+2h_s-s)\alpha_{ro}-\alpha_{rs}(bt+\lambda t_l+c_T+c_r-s)}{3\alpha_{rs}\alpha_{ro}}$, $k^{\text{YP}^*}=\frac{\alpha_{ro}(bt+c_r+c_s+2h_s-s)+\alpha_{rs}(-bt-h_s\alpha_{ro}-\lambda t_l+2c_T-c_r+s)}{3\alpha_{rs}}$ (in order to make the optimal solution not less than 0, $M>0$, where $M=(bt-\alpha_{rs}h_s+c_r+c_s+2h_s-s)\,\alpha_{ro}-\alpha_{rs}\,(bt+\lambda t_l+c_T+c_r-s)$).

Based on the above optimal decision, substituting it into the retail price, we can get: $p_{rs}^{\text{YP}^*}=\frac{(((1-\theta)h_s+\theta p_n+s)\alpha_{rs}+bt-s+c_r+c_s-2h_s)\alpha_{ns}+2h_s\alpha_{rs}\theta}{2\alpha_{ns}\alpha_{rs}}$, $p_{ro}^{\text{YP}^*}=\frac{\theta h_s}{\alpha_{ns}}+\frac{3\theta p_n+3s-(3\theta-2)h_s}{6}+\frac{2bt-2s+2c_r+2c_s+4h_s}{6\alpha_{rs}}+\frac{(bt-5\lambda t_l+c_T+c_r-s)}{6\alpha_{ro}}$.

In Model YA, the process of deriving the optimal decisions is similar to Model YP, hence, we omit it.

Comparing the remanufacturing firm's profits under Models YP and NP, we can get $\prod_F^{\text{YP}}-\prod_F^{\text{NP}}=\frac{(1-\rho)M^2}{36\theta\alpha_{rs}\alpha_{ro}(\alpha_{rs}-\alpha_{ro})}-T$, then we can get Theorem 4.1, where $\bar{T}^S=\frac{(1-\rho)M^2}{36\theta\alpha_{rs}\alpha_{ro}(\alpha_{rs}-\alpha_{ro})}$. □

A.2. Proof of Proposition 4.2

Proof. By analyzing the annual service fee threshold, we can get: $\frac{\partial\bar{T}^S}{\partial\alpha_{ro}}=\frac{1}{36\theta(\alpha_{ro}-\alpha_{rs})^2\alpha_{ro}^2}(\rho-1)\,M\big(\big(bt+\alpha_{rs}h_s+2\lambda t_l+2c_T+c_r-c_s-2h_s-s\big)\alpha_{ro}-\alpha_{rs}\,(bt+\lambda t_l+c_T+c_r-s)\big)$. Therefore, we have $N=\big(bt+\alpha_{rs}h_s+2\lambda t_l+2c_T+c_r-c_s-2h_s-s\big)\alpha_{ro}-\alpha_{rs}\big(bt+\lambda t_l+c_T+c_r-s\big)$. After merging λ, we get $N=\lambda t_l\,(2\alpha_{ro}-\alpha_{rs})+\big(bt+\alpha_{rs}h_s+2c_T+c_r-2h_s-s\big)\alpha_{ro}-\alpha_{rs}\,(bt+c_T+c_r-s)$.

When $\alpha_{ro}\le\frac{\alpha_{rs}}{2}$, the slope is negative. Then judge whether $C=\big(bt+\alpha_{rs}h_s+2c_T+c_r-c_s-2h_s-s\big)\alpha_{ro}-\alpha_{rs}\,(bt+c_T+c_r-s)$ is positive or negative. Note that, $C+M=-\lambda t_l\alpha_{rs}-2\,(\alpha_{rs}-\alpha_{ro})\,(bt+c_T+c_r-s)<0$, therefore, we have $C<0$. Therefore, when $\alpha_{ro}\le\frac{\alpha_{rs}}{2}$, $\frac{\partial\bar{T}^S}{\partial\alpha_{ro}}\ge 0$; when $\frac{\alpha_{rs}}{2}<\alpha_{ro}<1$, the slope is positive, if $\lambda\le\lambda_1$, $\frac{\partial\bar{T}^S}{\partial\alpha_{ro}}\ge 0$; otherwise, $\frac{\partial\bar{T}^S}{\partial\alpha_{ro}}<0$, where $\lambda_1=\frac{(bt+\alpha_{rs}h_s+2c_T+c_r-c_s-2h_s-s)\alpha_{ro}-\alpha_{rs}(bt+c_T+c_r-s)}{t_l(\alpha_{rs}-2\alpha_{ro})}$. □

A.3. Proof of Proposition 4.3

Proof. By analyzing the threshold of annual service fee, we can get: $\frac{\partial\bar{T}^S}{\partial t}=\frac{b(-1+\rho)M}{18\theta\alpha_{ro}\alpha_{rs}}\le 0$. □

A.4. Proof of Proposition 4.4

Proof. Through the analysis of total carbon emissions, we have $E^{\text{YP}^*}-E^{\text{NP}^*}=\frac{b(1-\rho)M}{6\theta\alpha_{rs}\alpha_{ro}}>0$. □

A.5. Proof of Proposition 4.5

Proof. By analyzing the optimal solution of retail price, we have: $p_{rs}^{\text{YP}^*}-p_{rs}^{\text{NP}^*}=0$; $p_{ro}^{\text{YP}^*}-p_{rs}^{\text{YP}^*}=\frac{(10h_s+s-bt-5\alpha_{rs}h_s-c_r-c_s)\alpha_{ro}+\alpha_{rs}(bt-5\lambda t_l+c_T+c_r-s)}{6\alpha_{ro}\alpha_{rs}}$. Therefore, when $\alpha_{ro}\le\bar{\alpha}_{ro}$, $p_{ro}^{\text{YP}^*}\le p_{rs}^{\text{YP}^*}$; when $\alpha_{ro}>\bar{\alpha}_{ro}$, if $\lambda\le\lambda_2$, $p_{ro}^{\text{YP}^*}\ge p_{rs}^{\text{YP}^*}$; otherwise, $p_{ro}^{\text{YR}^*}<p_{rs}^{\text{YR}^*}$. Note that, $\bar{\alpha}_{ro}=\frac{\alpha_{rs}(bt+c_T+c_r-s)}{bt+5\alpha_{rs}h_s+c_r+c_s-10h_s-s}$, $\lambda_2=\frac{\alpha_{ro}(10h_s+s-bt-5\alpha_{rs}h_s-c_r-c_s)+\alpha_{rs}(bt+c_T+c_r-s)}{5\alpha_{rs}t_l}$. □

A.6. Proof of Proposition 4.6

Proof. By analyzing the online and offline demand functions of remanufactured products, we can get: $D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}} - D_{rs}^{\mathrm{NP}} = \frac{(1-\rho)M}{6\theta\alpha_{rs}(\alpha_{ro}-\alpha_{rs})} < 0$; $D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}} + D_{nro}^{\mathrm{YP}} - D_{rs}^{\mathrm{NP}} = \frac{(1-\rho)M}{6\alpha_{ro}\alpha_{rs}\theta} > 0$. □

A.7. Proof of Theorem 4.7

Proof. $\prod_F^{\mathrm{YA}} - \prod_F^{\mathrm{NP}} = \frac{(1-\rho)B^2}{36\theta\alpha_{rs}\alpha_{ro}(\alpha_{rs}-\alpha_{ro})} - T$, where $B = M + 2\left(c_r - c_e\right)\left(\alpha_{ro} - \alpha_{rs}\right)$. When $T \leq \bar{T}^A$, it is better for the remanufacturing firm to enter the e-commerce platform; when $T > \bar{T}^A$, it is better not to enter the e-commerce platform, where $\bar{T}^A = \frac{(1-\rho)B^2}{36\theta\alpha_{rs}\alpha_{ro}(\alpha_{rs}-\alpha_{ro})}$. □

A.8. Proof of Proposition 4.8

Proof. $\bar{T}^A - \bar{T}^S = \frac{(c_e-c_r)(1-\rho)(M+(\alpha_{rs}-\alpha_{ro})(c_e-c_r))}{9\theta\alpha_{ro}\alpha_{rs}}$. Therefore, when $c_r = c_{rH}$, if $\alpha_{rs} \leq \bar{\alpha}_{rs}$, $\bar{T}^A \leq \bar{T}^S$; otherwise, $\bar{T}^A > \bar{T}^S$; when $c_r = c_{rL}$, $\bar{T}^A > \bar{T}^S$, where $\bar{\alpha}_{rs} = \frac{\alpha_{ro}(bt+2c_r+c_s+2h_s-c_e-s)}{bt+\alpha_{ro}h_s+\lambda t_l+c_T+2c_r-c_e-s}$. □

A.9. Proof of Proposition 4.9

Proof. $\prod_F^{\mathrm{YA}} - \prod_F^{\mathrm{YP}} = \frac{(c_e-c_r)(1-\rho)(M+(\alpha_{rs}-\alpha_{ro})(c_e-c_r))}{9\theta\alpha_{ro}\alpha_{rs}}$. Therefore, when $c_r = c_{rH}$, if $\alpha_{rs} \leq \bar{\alpha}_{rs}$, $\prod_F^{\mathrm{YP}} \geq \prod_F^{\mathrm{YA}}$, otherwise, $\prod_F^{\mathrm{YP}} < \prod_F^{\mathrm{YA}}$. When $c_r = c_{rL}$, $\prod_F^{\mathrm{YP}} < \prod_F^{\mathrm{YA}}$. □

A.10. Proof of Proposition 4.10

Proof. $p_{rs}^{\mathrm{YA}^*} - p_{rs}^{\mathrm{YP}^*} = 0$; $p_{ro}^{\mathrm{YA}^*} - p_{ro}^{\mathrm{YP}^*} = \frac{(c_e-c_r)(\alpha_{ro}-\alpha_{rs})}{3\alpha_{rs}\alpha_{ro}}$; $f^{\mathrm{YA}^*} - f^{\mathrm{YP}^*} = \frac{(c_e-c_r)(\alpha_{ro}-\alpha_{rs})}{3\alpha_{rs}\alpha_{ro}}$; $k^{\mathrm{YA}^*} - k^{\mathrm{YP}^*} = \frac{(c_e-c_r)(\alpha_{ro}-\alpha_{rs})}{3\alpha_{rs}}$. So when $c_r = c_{rH}$, $f^{\mathrm{YA}^*} \geq f^{\mathrm{YP}^*}$, $p_{ro}^{\mathrm{YA}^*} \geq p_{ro}^{\mathrm{YP}^*}$, $k^{\mathrm{YA}^*} \geq k^{\mathrm{YP}^*}$. When $c_r = c_{rL}$, $f^{\mathrm{YA}^*} < f^{\mathrm{YP}^*}$, $p_{ro}^{\mathrm{YA}^*} < p_{ro}^{\mathrm{YP}^*}$, $k^{\mathrm{YA}^*} < k^{\mathrm{YP}^*}$. □

A.11. Proof of Proposition 4.11

Proof. $D_{srs}^{\mathrm{YA}} + D_{nrs}^{\mathrm{YA}} - D_{srs}^{\mathrm{YP}} - D_{nrs}^{\mathrm{YP}} = \frac{(c_e-c_r)(\rho-1)}{3\alpha_{rs}\theta}$; $D_{srs}^{\mathrm{YA}} + D_{nrs}^{\mathrm{YA}} + D_{nro}^{\mathrm{YA}} - D_{srs}^{\mathrm{YP}} - D_{nrs}^{\mathrm{YP}} - D_{nro}^{\mathrm{YP}} = \frac{(c_e-c_r)(-1+\rho)(\alpha_{ro}-\alpha_{rs})}{3\alpha_{rs}\theta\alpha_{ro}}$. Therefore, when $c_r = c_{rH}$, $D_{srs}^{\mathrm{YA}} + D_{nrs}^{\mathrm{YA}} \geq D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}}$; when $c_r = c_{rL}$, $D_{srs}^{\mathrm{YA}} + D_{nrs}^{\mathrm{YA}} < D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}}$. When $c_r = c_{rH}$, $D_{srs}^{\mathrm{YA}} + D_{nrs}^{\mathrm{YA}} + D_{nro}^{\mathrm{YA}} \leq D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}} + D_{nro}^{\mathrm{YP}}$; when $c_r = c_{rL}$, $D_{srs}^{\mathrm{YA}} + D_{nrs}^{\mathrm{YA}} + D_{nro}^{\mathrm{YA}} > D_{srs}^{\mathrm{YP}} + D_{nrs}^{\mathrm{YP}} + D_{nro}^{\mathrm{YP}}$. □

A.12. Proof of Proposition 4.12

Proof. $E^{\mathrm{YA}^*} - E^{\mathrm{YP}^*} = \frac{(\alpha_{ro}-\alpha_{rs})(c_e-c_r)(-1+\rho)b}{3\alpha_{ro}\alpha_{rs}\theta}$. Therefore, when $c_r = c_{rH}$, $E^{\mathrm{YA}^*} \leq E^{\mathrm{YP}^*}$; when $c_r = c_{rL}$, $E^{\mathrm{YA}^*} > E^{\mathrm{YP}^*}$. □

A.13. Proof of extended models

Proof. In Model NPE, the profit function of the remanufacturing firm in the second period is

$$\prod_F^{\mathrm{NPE}} = D_{rs}^{\mathrm{NP}}\left(\alpha_{rs}\left(p_{rs} - c_r\right) + \left(1 - \alpha_{rs}\right)\left(s - c_r\right) - c_s - bt\right)$$
$$\text{s.t.} \quad 0 < D_{rs}^{\mathrm{NP}} \leq D_{ns}^{1}.$$

The optimization problem of Lagrange KKT condition in Model NPE is

$$L\left(p_{rs}, \mu_1, \mu_2\right) = D_{rs}^{\mathrm{NP}}\left(\alpha_{rs}\left(p_{rs} - c_r\right) + \left(1 - \alpha_{rs}\right)\left(s - c_r\right) - c_s - bt\right) + \mu_1 D_{rs}^{\mathrm{NP}} + \mu_2\left(D_{ns}^{1} - D_{rs}^{\mathrm{NP}}\right)$$
$$\text{s.t.} \quad \frac{\partial L\left(p_{rs}, \mu_1, \mu_2\right)}{\partial p_{rs}} = 0$$

$$\mu_1 D_{rs}^{\rm NP} = 0$$
$$\mu_2\left(D_{ns}^1 - D_{rs}^{\rm NP}\right) = 0.$$

Since the remanufactured product demands must satisfy the condition of $D_{rs}^{\rm NP} > 0$, therefore, we have the following two cases:

(a) When the quantity constraint of the manufactured products is binding, *i.e.*, $D_{ns}^1 = D_{rs}^{\rm NP}$, we have $\mu_1 = 0$, $\mu_2 > 0$, and the optimal decisions in Model NPE are: $p_{rs}^{\rm NPE^*} = \frac{\left(1+h_s-p_n\right)\alpha_{ns}-2h_s\right)\theta^2\alpha_{rs}{}^2-\alpha_{ns}\alpha_{rs}\left(\left(\left(1+2h_s-2p_n\right)\theta-h_s\right)\alpha_{ns}-4\theta h_s\right)-2h_s\alpha_{ns}{}^2}{\alpha_{ns}{}^2\alpha_{rs}}$.

(b) When the quantity constraint of remanufactured products is not binding, *i.e.*, $D_{rs}^{\rm NP} < D_{ns}^1$, we have $\mu_1 = 0$, $\mu_2 = 0$, and the optimal decisions are the same as those under Model NP, thus, we omit it.

Note that, the process of deriving the optimal decisions under Models YPE and YAE are similar to Model NPE, thus, we omit it.

In Model YPE, when the quantity constraint of the remanufactured products is binding, the optimal decisions are:

$$\begin{aligned}
f^{\rm YPE^*} = &\frac{1}{3\alpha_{ns}{}^2\alpha_{ro}}((\theta(\alpha_{rs}-\alpha_{ro})(2+3h_s-3p_n)+(s-h_s)\alpha_{rs}-s\alpha_{ro}\\
&-\lambda t_l - c_T + c_s + 2h_s)\alpha_{ns}{}^2 + 2\theta\alpha_{ns}(\alpha_{ro}-\alpha_{rs})(\theta\alpha_{rs}(1+h_s-p_n)+3h_s)\\
&+4\alpha_{rs}h_s\theta^2(\alpha_{rs}-\alpha_{ro}))\\
k^{\rm YPE^*} = &\frac{1}{3\alpha_{ns}{}^2}((\theta(\alpha_{rs}-\alpha_{ro})(2+3h_s-3p_n)+(s-h_s)\alpha_{rs}-s\alpha_{ro}\\
&-\lambda t_l + 2c_T + c_s + 2h_s)\alpha_{ns}{}^2 + 2\theta\alpha_{ns}(\alpha_{ro}-\alpha_{rs})(\theta\alpha_{rs}(1+h_s-p_n)+3h_s)\\
&+4\alpha_{rs}h_s\theta^2(\alpha_{rs}-\alpha_{ro}))\\
p_{ro}^{\rm YPE^*} = &\frac{1}{6\alpha_{ns}{}^2\alpha_{ro}((1-\rho)\alpha_{rs}(\alpha_{ns}+\theta(\alpha_{ro}-\alpha_{rs}))+\rho\alpha_{ns}\alpha_{ro})}(\alpha_{ro}{}^2(\rho\alpha_{ns}\\
&+(1-\rho)\theta\alpha_{rs})(4\alpha_{rs}\theta^2((1+h_s-p_n)\alpha_{ns}-2h_s)-\alpha_{ns}\theta((4+9h_s-9p_n)\alpha_{ns}\\
&-18h_s)+s\alpha_{ns}{}^2)+\alpha_{ro}(\alpha_{ns}{}^3((((9h_s-9p_n+4)\rho-12h_s+12p_n-6)\theta\\
&-(s-h_s)\rho)\alpha_{rs}+\rho(c_T-c_s-2h_s-5\lambda t_l))+\alpha_{ns}{}^2\alpha_{rs}\theta((((13p_n-13h_s-8)\theta\\
&+s-h_s)\rho+(15h_s-15p_n+10)\theta-s+h_s)\alpha_{rs}+(5\lambda t_l-c_T+c_s-16h_s)\rho\\
&-5\lambda t_l+c_T-c_s+22h_s)+\theta^2\alpha_{rs}{}^2\alpha_{ns}(4\alpha_{rs}\theta(\rho-1)(1+h_s-p_n)+2h_s(13\alpha\\
&-15))+8(1-\rho)\alpha_{rs}{}^3h_s\theta^3)-6\alpha_{ns}{}^2\alpha_{rs}\lambda t_l(1-\rho)(\alpha_n-\theta\alpha_{rs})\\
p_{rs}^{\rm YPE^*} = &\frac{1}{6\alpha_{ns}{}^2\alpha_{rs}((1-\rho)\alpha_{rs}(\alpha_{ns}+\theta(\alpha_{ro}-\alpha_{rs}))+\rho\alpha_{ns}\alpha_{ro})}(4\theta^3\alpha_{rs}{}^4\\
&\times(\rho-1)(1+h_s-p_n)-2h_s)+(\rho-1)\theta\alpha_{rs}{}^3(((13p_n-13h_s-8)\theta+s\\
&+5h_s)\alpha_{ns}{}^2-\theta\alpha_{ns}(4\alpha_{ro}\theta(1+h_s-p_n)-26h_s)+8\alpha_{ro}h_s\theta^2)-\alpha_{ns}\alpha_{rs}{}^2\\
&\times((\rho-1)\alpha_{ns}{}^2((9p_n-9h_s-4)\theta+s+5h_s)+\alpha_{ro}h_s\theta^2(26\alpha-14)\theta\alpha_{ns}\\
&\times((((13p_n-13h_s-8)\theta+s+6h_s)\alpha+(7h_s-7p_n+2)\theta-s-6h_s)\alpha_{ro}\\
&+(\rho-1)(28h_s+\lambda t_l+c_T-c_s)))+\alpha_{ns}{}^2\alpha_{rs}(((((9p_n-9h_s-4)\theta+s\\
&+6h_s)\rho+(3p_n-3h_s-2)\theta-s)\alpha_{ro}+(\rho-1)(10h_s+\lambda t_l+c_T-c_s))\alpha_{ns}\\
&+\alpha_{ro}h_s\theta(30\alpha-6))-12\rho h_s\alpha_{ns}{}^3\alpha_{ro}).
\end{aligned}$$

In Model YAE, when the production quantity constraint of the remanufactured products is binding, optimal decisions are:

$$f^{\rm YAE^*} = \frac{1}{3\alpha_{ns}{}^2\alpha_{ro}}((\theta(\alpha_{rs}-\alpha_{ro})(2+3h_s-3p_n)+(s-h_s)\alpha_{rs}-s\alpha_{ro}$$

$$
\begin{aligned}
&- \lambda t_l - c_T + c_s + 2h_s)\alpha_{ns}{}^2 + 2\theta\alpha_{ns}(\alpha_{ro} - \alpha_{rs})(\theta\alpha_{rs}(1 + h_s - p_n) + 3h_s)\\
&+ 4\alpha_{rs}h_s\theta^2(\alpha_{rs} - \alpha_{ro}))\\
k^{\mathrm{YAE}^*} = {}& \frac{1}{3\alpha_{ns}{}^2}((\theta(\alpha_{rs} - \alpha_{ro})(2 + 3h_s - 3p_n) + (s - h_s)\alpha_{rs} - s\alpha_{ro} - \lambda t_l\\
&+ 2c_T + c_s + 2h_s)\alpha_{ns}{}^2 + 2\theta\alpha_{ns}(\alpha_{ro} - \alpha_{rs})(\theta\alpha_{rs}(1 + h_s - p_n) + 3h_s)\\
&+ 4\alpha_{rs}h_s\theta^2(\alpha_{rs} - \alpha_{ro}))\\
p_{ro}^{\mathrm{YAE}^*} = {}& \frac{1}{6\alpha_{ns}{}^2\alpha_{ro}((1-\rho)\alpha_{rs}(\alpha_{ns} + \theta(\alpha_{ro} - \alpha_{rs})) + \rho\alpha_{ns}\alpha_{ro})}(\alpha_{ro}{}^2(\rho\alpha_{ns}\\
&+ (1-\rho)\theta\alpha_{rs})(4\alpha_{rs}\theta^2((1 + h_s - p_n)\alpha_{ns} - 2h_s) - \alpha_{ns}\theta((4 + 9h_s - 9p_n)\alpha_{ns}\\
&- 18h_s) + s\alpha_{ns}{}^2) + \alpha_{ro}(\alpha_{ns}{}^3((((9h_s - 9p_n + 4)\rho - 12h_s + 12p_n - 6)\theta\\
&- (s - h_s)\rho)\alpha_{rs} + \rho(c_T - c_s - 2h_s - 5\lambda t_l)) + \alpha_{ns}{}^2\alpha_{rs}\theta((((13p_n - 13h_s - 8)\theta\\
&+ s - h_s)\rho + (15h_s - 15p_n + 10)\theta - s + h_s)\alpha_{rs} + (5\lambda t_l - c_T + c_s - 16h_s)\rho\\
&- 5\lambda t_l + c_T - c_s + 22h_s) + \theta^2\alpha_{rs}{}^2\alpha_{ns}(4\alpha_{rs}\theta(\rho - 1)(1 + h_s - p_n) + 2h_s(13\alpha\\
&- 15)) + 8(1-\rho)\alpha_{rs}{}^3h_s\theta^3) - 6\alpha_{ns}{}^2\alpha_{rs}\lambda t_l(1-\rho)(\alpha_n - \theta\alpha_{rs})\\
p_{rs}^{\mathrm{YAE}^*} = {}& \frac{1}{6\alpha_{ns}{}^2\alpha_{rs}((1-\rho)\alpha_{rs}(\alpha_{ns} + \theta(\alpha_{ro} - \alpha_{rs})) + \rho\alpha_{ns}\alpha_{ro})}(4\theta^3\alpha_{rs}{}^4\\
&\times(\rho - 1)(1 + h_s - p_n) - 2h_s) + (\rho - 1)\theta\alpha_{rs}{}^3(((13p_n - 13h_s - 8)\theta + s\\
&+ 5h_s)\alpha_{ns}{}^2 - \theta\alpha_{ns}(4\alpha_{ro}\theta(1 + h_s - p_n) - 26h_s) + 8\alpha_{ro}h_s\theta^2) - \alpha_{ns}\alpha_{rs}{}^2\\
&\times((\rho - 1)\alpha_{ns}{}^2((9p_n - 9h_s - 4)\theta + s + 5h_s) + \alpha_{ro}h_s\theta^2(26\alpha - 14)\theta\alpha_{ns}\\
&\times((((13p_n - 13h_s - 8)\theta + s + 6h_s)\alpha + (7h_s - 7p_n + 2)\theta - s - 6h_s)\alpha_{ro}\\
&+ (\rho - 1)(28h_s + \lambda t_l + c_T - c_s))) + \alpha_{ns}{}^2\alpha_{rs}(((((9p_n - 9h_s - 4)\theta + s\\
&+ 6h_s)\rho + (3p_n - 3h_s - 2)\theta - s)\alpha_{ro} + (\rho - 1)(10h_s + \lambda t_l + c_T - c_s))\alpha_{ns}\\
&+ \alpha_{ro}h_s\theta(30\alpha - 6)) - 12\rho h_s\alpha_{ns}{}^3\alpha_{ro}).
\end{aligned}
$$

Comparing the remanufacturing firm's optimal profits under Models NPE and YPE, we have: $\prod_F^{\mathrm{YPE}} - \prod_F^{\mathrm{NPE}} = \frac{(1-\rho)\alpha_{rs}C^2}{36\theta(\alpha_{rs}-\alpha_{ro})\alpha_{ns}{}^3((1-\rho)(\alpha_{ns}+\theta(\alpha_{ro}-\alpha_{rs}))\alpha_{rs}+\rho\alpha_{ns}\alpha_{ro})} - T$.

Therefore, we could obtain the conclusion of Remark 5.1, where $\bar{T}^{\mathrm{SE}} = \frac{(1-\rho)\alpha_{rs}C^2}{36\theta(\alpha_{rs}-\alpha_{ro})\alpha_{ns}{}^3((1-\rho)(\alpha_{ns}+\theta(\alpha_{ro}-\alpha_{rs}))\alpha_{rs}+\rho\alpha_{ns}\alpha_{ro})}$ and $C = \alpha_{ns}{}^2\big(\big(2 + 3h_s - p_n\big)\big(\alpha_{ro} - \alpha_{rs}\big)\theta + (h_s - s)\,\alpha_{rs} + s\alpha_{ro} + \lambda t_l + c_T - c_s - 2h_s\big) + 4\alpha_{rs}h_s\theta^2\,(\alpha_{ro} - \alpha_{rs}) - 2\theta\alpha_{ns}\,(\alpha_{ro} - \alpha_{rs})\,\big((1 + h_s - p_n)\,\theta\alpha_{rs} + 3h_s\big)$.

Comparing the remanufacturing firm's optimal profits under Models NPE and YAE, we have: $\prod_F^{\mathrm{YAE}} - \prod_F^{\mathrm{NPE}} = \frac{(1-\rho)\alpha_{rs}C^2}{36\theta(\alpha_{rs}-\alpha_{ro})\alpha_{ns}{}^3((1-\rho)(\alpha_{ns}+\theta(\alpha_{ro}-\alpha_{rs}))\alpha_{rs}+\rho\alpha_{ns}\alpha_{ro})} - T$.

Therefore, we could obtain the conclusion of Remark 5.2, where $\bar{T}^{\mathrm{AE}} = \frac{(1-\rho)\alpha_{rs}C^2}{36\theta(\alpha_{rs}-\alpha_{ro})\alpha_{ns}{}^3((1-\rho)(\alpha_{ns}+\theta(\alpha_{ro}-\alpha_{rs}))\alpha_{rs}+\rho\alpha_{ns}\alpha_{ro})}$.

Besides, it is easy to obtain that $\bar{T}^{\mathrm{SE}} = \bar{T}^{\mathrm{AE}}$. □

Acknowledgements. This research is partly supported by the National Natural Science Foundation of China (Grant Nos. 71801121; 72061024), the National Social Science Foundation of China (Grant No. 21CGL025), and the College of Humanities & Social Science Research Base Project of Jiangxi Province (2020) (Grant No. JD20099).

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