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A hybrid trade-old-for-new and trade-old-for-remanufactured supply chain with carbon tax

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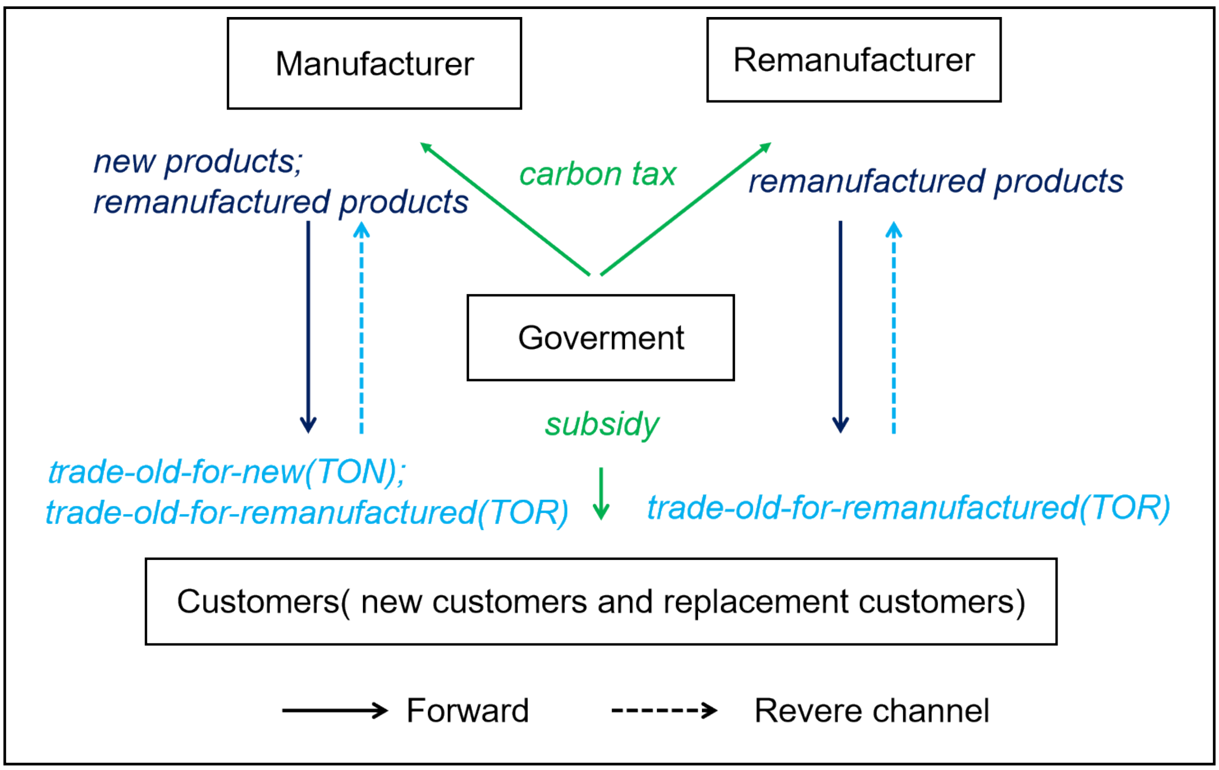
Graphical abstract



Analyzing the influence of remanufacturer competition and carbon tax on the manufacturer's decisions and the environment in a hybrid trade-old-for-new and trade-old-for-remanufactured supply chain.

Public summary

- This paper analyzes the TON and TOR optimal decisions of manufacturer in a competitive market, and explores the impact of remanufacturer providing TOR on manufacturer.
- This paper formulates three profit maximization models and presents some theoretical and numerical analyses. Further exploring the impact of residual value, consumer willingness to products and carbon tax on the TON and TOR decisions of manufacturer.
- This paper investigates the TON and TOR decisions under the carbon tax policy. We find that a higher carbon tax rate may increase the manufacturer's profit due to the increase in TOR demand.

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Abstract: Facing serious environmental problems, governments and manufacturers are taking action to reduce carbon emissions. Among these endeavors, carbon tax policy are widely adopted by governments, trade-old-for-new (TON) and trade-old-for- remanufactured (TOR) are offered by manufacturers and subsidized by governments. To explore the effects of remanufacturer competition and carbon tax on the manufacturer's TON and TOR decisions and the environment, we formulate three profit maximization models and present some theoretical and numerical analyses. The results show that, under the remanufacturer competition and carbon tax, the manufacturer's optimal price and production decisions mainly depend on consumer willingness and carbon tax rate. A higher consumer willingness to manufacturer's remanufactured products will decrease the demand for the manufacturer's TON, but it always increases the demand foe the manufacturer's TOR. A higher consumer willingness to remanufacturer's products will not affect the demand for the manufacturer's TON; however, it will reduce the demand for manufacturer's TOR. In addition, we find that a higher carbon tax rate always reduces total carbon emission reduction, and it may increase the manufacturer's profit due to the increase in TOR demand.

Keywords: trade-old-for-new; trade-old-for-remanufactured; remanufacturer competition; carbon tax; consumer willingness

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1 Introduction

Environmental problems are becoming increasingly serious, and global warming has led to a sharp increase in the probability of natural disasters and human diseases[1]. Carbon emissions are considered to be the main cause of climate change, to curb emissions of greenhouse gases, international organizations have introduced a series of conventions and policies, such as United Nations' Framework Convention on Climate Change, and the Kyoto Protocol. Around the world, governments are actively responding to the convention, controlling carbon emissions, and enforcing a series of carbon laws and policies, such as mandatory carbon emissions capacity, carbon emissions cap and trade, carbon tax, and low-carbon offset[2,3]. In 2005, the European Union Emissions Trading System (EU-ETS) first implemented a CO_2 cap-and-trade system[4]. Before that, Finland, Poland, and Denmark introduced carbon tax policy to limit carbon emissions by 1992[5]. Carbon emissions cap and trade policy is widely adopted, however, carbon tax policy can stably promote remanufacturing and effectively curb carbon emissions[7]. Hence, we consider the carbon tax policy and take the carbon emission cost as a part of the production cost in our paper.

Under the pressure of government policies and social responsibility, enterprises are also actively seeking to reduce carbon emissions during operation. To reduce carbon emissions, manufacturers have explored many initiatives, such as recycling and remanufacturing. Trade-old-for-new (TON) is an effective way for recycling. In TON program, consumers buy new products at discounted prices through trading in old products, which is often encouraged by the government. To reflect this, the government offers a subsidy for each replacement. A case in point is that the Chinese government launched the TON subsidy policy for household appliances and cars in 2009, which was responded by Haier, Geely, Suning and other enterprises[6,7]. TON is widely implemented in mobile phone, automobile, computer and other industries[6], which promotes the marketing of new products and improves consumers' awareness of environmental protection. To promote recycling and the demand for remanufactured products, some enterprises implement trade-old-for-remanufactured (TOR). TOR encourages consumers to replace existing products and buy remanufactured products at discounted prices[8]. In 2013, the Chinese government announced pilot TOR programs, and 10 automobile and engine manufacturers were chosen[9,10]; In 2015, a subsidy policy was further implemented in the TOR program[11].

Based on the background above, some manufacturers can offer TON and TOR programs together. For example, some manufacturers offer TOR program, while some TOR pilot manufacturers have provided customers with TON service, such as FAW Volkswagen, Weichai, Yuchai, and DCEC[9]. Facing the coexistence of TON and TOR programs as well as competition from the remanufacturer providing TOR services, customers have multiple purchase options. New consumers are the first-time buyers and make purchase decisions according to the utility from purchasing products: manufacturer's new products; manufacturer's remanufactured products; remanufacturer's remanufactured products. Replacement customers have owned used products and either keep the existing products, or trade old for new products of the manufacturer; trade old for remanufacturer products of the manufacturer; trade old for remanufacturer products of the remanufacturer.

Considering the importance of carbon tax regulations and the universality of enterprises implementing TON and TOR programs, as well as the competition among manufacturers, we study the coexistence of TON and TOR under carbon tax and manufacturer competition, and mainly answer the following specific questions: (1) Under what circumstances should manufacturers implement TON and TOR programs? What are the optimal pricing and production strategies? (2) How does the implementation of the TOR program by remanufacturer affect the TON and TOR programs of manufacturers? What is the impact of customers' willingness coefficients of different products on manufacturer and total carbon emissions? (3) How does the carbon tax affect the manufacturer and total carbon emissions with remanufacturer competition? What is the government's best strategy?

To explore the above problems, we first established a basic model of TON and TON program provided by the manufacturer, defined as Model O. Then, the manufacturer competes with a remanufacturer, who provides the TOR program, defined as Model R. Finally, based on Model R, considering the carbon tax policy, we obtain Model C. By comparing the model and numerical analysis, we find that under remanufacturer competition and carbon tax, the optimal price and production decision are affected by many factors, including the willingness of consumers and the carbon tax rate. In addition, we find that the increase of carbon tax rate not only reduces carbon emissions, but also increases the manufacturer's profits, which is mainly due to the increase of demand of remanufactured products from manufacturer in a competitive environment. The contributions of our paper are mainly in three aspects. First, we discuss the impact of remanufacturer competition on manufacturer and obtain the optimal TON and TOR schemes of manufacturer. Second, we further investigate the TON and TOR schemes under the carbon tax, and analyze the total carbon emissions of the supply chain. Finally, we analyze the impact of consumers' willingness to purchase different products on manufacturers' profits and total carbon emissions.

The remainder of our paper is organized as follows. Section 2 reviews the previous literature. Section 3 gives model assumptions and introduces three models: Model O, Model R and Model C. Section 4 is a numerical experiment, that analyzes the impact of residual value, consumer willingness coefficients and carbon tax rate on manufacturer and total carbon emissions. Section 5 summarizes the paper. All proofs can be found in Appendix A.

2 Literature review

Our research is closely related to TON and TOR. We will review the literature from the following aspects: Trade-old-for-new (TON); Trade-old-for-remanufactured (TOR); The coexistence of TON and TOR programs; Trade-in under carbon regulation; Remanufacturing closed-loop supply chain.

Ton and TOR programs have received considerable research attention, most of which focuses on optimal pricing and production and the conditions of implementing TON and TOR programs. Feng[12] studied the interaction mechanism among the trade-in program, price strategy, and product quality choice. Hong et al.[13] constructed game modes under different supply chain dominant roles and different trade-in service providers, and they found that both the manufacturer and the retailer prefer to provide trade-in service themselves when there is no transfer payment. Wang[11] studied three "trade-in" closed-loop supply chain models: bilateral monopoly between retailers and manufacturers, competition between remanufacturers and recyclers, and competition between recyclers when green consumers appear in the market. Han et al.[8] evaluated the conditions for a firm to offer a TOR program and to best implement it, they found that remanufactured product receptivity and new product durability should satisfy certain conditions, and high product remanufacturability and government subsidies are strong incentives.

Some scholars have conducted research on the coexistence of TON and TOR programs, further exploring the feasibility and enthusiasm of enterprises to provide trade in programs. Ma et al.[9] studied a firm's optimal pricing decisions and identified the thresholds for firms to offer TON and TOR under the coexistence of TON and TOR programs, and showed that firms should use different trade-in schemes under different conditions. Bo[14] focused on the government subsidy policy and studied how the government provides subsidies for TON programs and TOR programs. Du et al.[15] explored the impact of replacement recycling prices, government subsidies, used products' residual value and remanufacturing capabilities on product pricing, production decisions and profitability under the coexistence of TON and TOR programs. Zhu[16] investigated the optimal pricing and production strategy of a hybrid trade old for new and remanufactured product supply chain under the constraint of consumer participation, and obtained the performance of new and remanufactured products on both primary and replacement markets. These articles neglected the carbon emission costs of manufacturers.

Carbon emission reduction in manufacturing has always been an important problem, and many scholars have gradually considered TON and TOR programs under the constraint of carbon reduction policies. Miao et al.[17] considered remanufacturing with trade-ins under carbon emissions regulations, they showed that the introduction of carbon regulations can promote sales of remanufactured products, and firm's profit will be lost due to emission costs but can be compensated by government subsidies. Shu et al.[7] established the trade-old-for-remanufactured (TOR) model with carbon tax and government subsidies, and found that appropriate carbon tax and government subsidies can curb carbon emissions and in-

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crease profits for enterprises. Shu et al.[18] explored the recycling and remanufacturing decisions under carbon emission constraints and corporate social responsibility, and suggested that governments formulate rational carbon emission caps for enterprises with different coefficients of remanufacturing and emission reduction. Based on different consumer willingness and product durability, Huang[19] established a TOR model under carbon tax, carbon trading, and government subsidies, and they found that formulating appropriate carbon policies and government subsidy policies, corporate profits can be increased while reducing carbon emissions. Luo et al.[1] developed four game-theoretic models to evaluate the impact of carbon tax policy on manufacturing and remanufacturing decisions in a closed-loop supply chain, and found that carbon tax can effectively promote manufacturers to invest in carbon reduction technology, but it may demotivate manufacturers to remanufacture if carbon tax is not reasonable.

Trade-in is often closely related to remanufacturing closed-loop supply chains, which have attracted great attention from many academic researchers. Remanufacturing closed-loop supply chains mainly discuss two aspects: collecting mode selection problem; the undertaker of remanufacturing activit. Chen et al.[20] investigated the three collecting modes in the green supply chain under the reward-penalty mechanism from the government, and they found that manufacturer collection is more effective when transfer is not high. Yang et al.[21] investigated the optimal collection mode for the manufacturer under cap-and-trade regulation, and showed that the third-party collection mode is preferred. Dou et al.[22] analyzed retailer collects (R-collect) and manufacturer collects (M-collect) with green technology (GT) and trade-in program and showed that governments should advocate the "M-collect with GT" and "R-collect without GT" schemes. Wang et al.[23] studied the three manufacturers' recycling choices: recycling rejection, self-implementation collecting and outsourcing collecting, and found that the manufacturer will always choose to recycle and remanufacturing, whose collecting channel depends on the unit cost of self-collecting and the compensation from outsourcing-collecting. Zhu et al.[6] developed a production and trade-in pricing framework in the presence of duopoly competition and studied the equilibrium decision problem in two competitive scenarios: only one manufacturer implementing the trade-in strategy and two manufacturers simultaneously implementing the trade-in strategy. Recently, some scholars have associated TON and TOR problems with remanufacturing closed-loop supply chains. JIN et al.[24] considered the TON manufacturer and the associated TOR remanufacturer, they found that the consumer market of TOR cannibalizes the consumer market of TON when the replacement recycling price increases. In our paper, we considered that the manufacturer offers TON and TOR, while a competitive remanufacturer offers TOR in the supply chain.

In this paper, we also discuss the optimal pricing and production strategies when the manufacturer offers TON and TOR together. However, unlike the above literature, we focus on the following questions. First, the previous literature seldom considers the manufacturer in a competitive environment. We study the coexistence of TON and TOR programs with the competition of remanufacturer and analyze the impact of remanufacturers providing TOR on manufacturer. Second, based on the competitive environment, we consider the impact of carbon tax policy on manufacturer and car- bon emissions. Finally, we also analyzed the impact of consumers' willingness to manufacturers' and remanufacturers' products on manufacturers and carbon emissions.

3 Materials and research methods

3.1 Problem description and symbol instruction

This study considers a closed-loop supply chain composed of a single manufacturer and a single remanufacturer, in which the manufacturer produces both new and remanufactured products and offers TON and TOR, and the remanufacturer produces remanufactured products and offers TOR only. To promote the development of a low-carbon economy, the government implements a carbon tax regulation, and manufacturers and remanufacturers recycle consumers' existing products at different prices and sell remanufactured products to consumers. In this model, the manufacturer is the Stackelberg leader, the remanufacturer is the follower, and the government offers an additional subsidy to consumers when they participate in TON or TOR programs. This closed-loop supply chain model is shown in Fig. 1, the parameters and variables involved in the models are shown in Table 1.

3.2 Assumptions

To better understand our model, the key assumptions are shown as follows:

Assumption 1. The manufacturer produces a new product at a unit production cost c_{mn}, and a remanfactured product at a unit remanufacturing cost c_{mr}.The manufacturer can save production costs from remanufacturing[8], i.e., $c_{mn} > c_{mr}$.The remanufacturer produces a remanufactured product at a unit remanufacturing cost c_{rr}.

Assumption 2. The trade-in rebate from manufacturer and remanufacturer respectively at price p_{mo} and p_{ro}. The manufacturer offers new products at a unit price p_{mn}, and offers remanufactured products at p_{mr}. The remanufacturer offers remanufactured products at p_{rr}.

Assumption 3. New and remanufactured products are available for customers, and they have the same function, quality and utility, but consumers have different preferences for them[11,17]. Consumers are heterogeneous with respect to their willingness-to-pay θ, which is distributed in [0, 1]. Customers value the new products at θ, while they value the remanufactured products from manufacturer at $\delta_m\theta$. Customers value the remanufactured products from remanufacturer at $\delta_r\theta$. Since the manufacturer has a brand effect in the market, we assume that consumers perceive the manufacturer's remanufactured products to be of higher value[1], i.e. $\delta_m > \delta_r$. For replacement customers, they value their used products at $\delta_o\theta$.

Assumption 4. Normalizing all customers in the market to one, we assume that there are α new customers and 1-α replacement customers, where $0<\alpha<1$. These two customer groups act independently, and costumers make purchase decisions according to the utilities they can obtain from the products.

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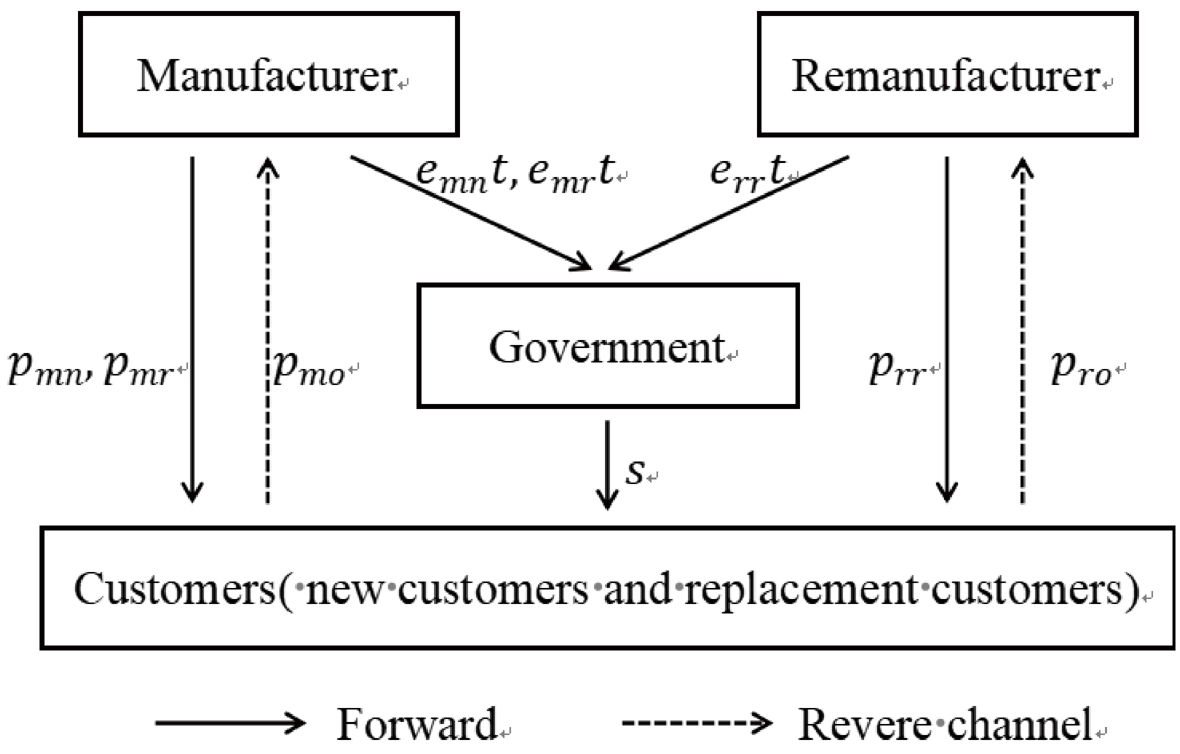

Fig. 1. A hybrid TON and TOR supply chain with remanufacturer competition and carbon tax.

Assumption 5. The government offers a subsidy to consumers who participate in TON or TOR, which can be denoted as s.

Assumption 6. Remanufacturing could reduce associated carbon emissions due to the energy and raw material savings[3,25,26]. We define the carbon tax imposed on the manufacturer/remanufacturer as the additional linear cost associated with the carbon emissions[17]. The carbon emission of a new product (a remanufactured product) of the manufacturer is $e_{mn}(e_{mr})$, while that of a remanufactured product of the remanufacturer is e_{rr}. In addition, t represents the rate of carbon tax.

3.3 The coexistence of TON and TOR programs (Model O)

Initially, TON and TOR programs without remanufacturer competition and carbon tax are explored. Remanufacturing with trade-ins has been studied by Miao et al.[17], which is the model reference for our paper. The model O is the reference model used to distinguish between the impacts of remanufacturer competition and carbon tax on enterprises and the environment. For new customers, they get a utility $U^n_{mn} = \theta - p_{mn}$ from the new product and a utility $U^n_{mr} = \delta_m\theta - p_{mr}$ from the remanufactured product. If $U^n_{mn} > 0$ and $U^n_{mn} > U^n_{mr}$ the customer buys new product, otherwise buys remanufactured product if $U^n_{mr} > 0$. For replacement customers, they get a utility $U^r_{mn} = \theta - p_{mn} + p_{mo} + s$ from the new product and a utility $U^r_{mr} = \delta_m\theta - p_{mr} + p_{mo} + s$ from the remanufactured product. If $U^r_{mn} > \delta_o\theta$ and $U^r_{mn} > U^r_{mr}$ the customer buys new product, otherwise buys remanufactured product if $U^r_{mr} > \delta_o\theta$.

The target of the manufacturer is to maximize its total profits, and the Model O can be expressed as:

$$\max \pi_M = (p_{mn} - c_{mn})(Q^n_{mn} + Q^r_{mn}) + (p_{mr} - c_{mr})(Q^n_{mr} + Q^r_{mr}) \\ (p_{mo} - v)(Q^r_{mn} + Q^r_{mr})) \\ \text{s.t.} \begin{cases} Q^n_{mn} > 0 \\ Q^n_{mr} > 0 \\ Q^r_{mn} > 0 \\ Q^r_{mr} > 0 \end{cases} \tag{1}$$

In function (1), $(p_{mn} - c_{mn})(Q^n_{mn} + Q^r_{mn})$ and $(p_{mr} - c_{mr}) \cdot (Q^n_{mr} + Q^r_{mr})$ represent the profits from selling new products and remanufactured products respectively, and $p_{mo}(Q^r_{mn} + Q^r_{mr})$ is the total cost of trade-in. The constraint implies that some new customers buy new products and others buy remanufactured products, some replacement customers trade-in new products and others trade-in remanufactured products. We provide the manufacturer's optimal pricing and production policy in Proposition 1.

Proposition 1. When $Q^{n*}_{mr} > 0$ and $Q^{r*}_{mr} > 0$, the new customers and replacement customers not only purchase new products, but also purchase remanufactured products. The manufacturer's optimal pricing and production policy can be described as follows:

① The manufacturer's pricing policy is $p^*_{mn} = \dfrac{1 + c_{mn}}{2}$, $p^*_{mr} = \dfrac{\delta_m + c_{mr}}{2}$, and $p^*_{mo} = \dfrac{\delta_o + v + s}{2}$.

② The manufacturer's production policy is $Q^{n*}_{mn} = \alpha\left(1 - \dfrac{c_{mn} - c_{mr}}{1 - \delta_m}\right)$, $Q^{n*}_{mr} = \alpha\left(\dfrac{\delta_m c_{mn} - c_{mr}}{2\delta_m(1 - \delta_m)}\right)$, $Q^{r*}_{mn} = \left(\dfrac{1 - \alpha}{2}\right) \cdot \left(1 - \dfrac{c_{mn} - c_{mr}}{1 - \delta_m}\right)$, and

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Table 1. Parameter notations.

Given parameters	
$\alpha(0<\alpha<1)$	All customers in the market is one, α customers, $1-\alpha$ replacement customers
$\theta(0<\theta<1)$	Customer's value evaluation of new products
δ_m	Customer's preference coefficient for remanufactured products from manufacturer
δ_r	Customer's preference coefficient for remanufactured products from remanufacturer
δ_o	The salvage value of the used products
c_{mn}/c_{mr}	Unit production cost of new/ remanufactured products from manufacturer
c_{rr}	Unit production cost of remanufactured products from remanufacturer
s	An TON or TOR subsidy from government for customer
e_{mn}/e_{mr}	Unit carbon emission of new/ remanufactured products from manufacturer
e_{rr}	Unit carbon emission of remanufactured products from remanufacturer
t	Carbon tax rate
Decision parameters	
p_{mo}/p_{ro}	The trade in rebate from manufacturer/ remanufacturer
p_{ij}	The price of product j of i ($i=m$: manufacturer; $r=$ remanufacturer; $j=n$: new products; r: remanufactured products) from replacement customers
Q^n_{ij}	The demand of product j of i ($i=$ m:manufacturer; $r=$ remanufacturer; $j=n$: new products; r: remanufactured products) from new customers
Q^r_{ij}	The demand of product j of i ($i=m$: manufacturer; $r=$ remanufacturer; $j=n$: new products; r: remanufactured products) from replacement customers
$\pi_M \pi_{RM}$	The total profit of manufacturer/remanufacturer
C(e)	The total carbon emission of supply chain

$$Q^{r*}_{mr}=\left(\frac{1-\alpha}{2}\right)\left(\frac{(\delta_m-\delta_o)c_{mn}-(1-\delta_o)c_{mr}+(1-\delta_o(V+s)}{(\delta_m-\delta_o)(1-\delta_m)}\right).$$

Proposition 1 describes the optimal strategy for TON and TOR programs. When the value of the used products for the firm and government subsidy are fixed, the manufacturer's optimal decisions depend on the cost structures of the new and the remanufactured products, the salvage value of the used products and the customer's preference coefficient for remanufactured products. The price of products is positively related to their cost, and the production of new products and remanufactured products is mainly determined by the cost structures. We can observe that the prices of remanufactured products are increasing in the customer's preference coefficient for remanufactured products. Intuitively, if customers' preference coefficient for remanufactured products is low, enterprises should lower the price to ensure that customers participate in the purchase of remanufactured products. At the same time, the trade-in rebate provided by the enterprise depends on the residual value of the used product from the replacement customer. According to Proposition 1, it is clear that new customers' purchase intentions are closely related to the customer's preference coefficient for remanufactured products. The number of replacement customers participating in the TON program is affected by the cost and customer's preference coefficient for remanufactured products, while participating in TOP is also affected by the salvage value of the used products.

3.4 TON and TOR programs with remanufacturer competition (Model R)

This part considers the impacts of remanufacturer competition on the optimal strategies of the manufacturer. In model R, the remanufacturer can offer the TOR. For new customers, if they choose the manufacturer, they get utility $U^n_{mn}=\theta-p_{mn}$ from the new product and utility $U^n_{mr}=\delta_m\theta-p_{mr}$ from the remanufactured product, however they get utility $U^n_{rr}=\delta_r\theta-p_{rr}$ of purchasing remanufactured products from remanufacturer. If $U^n_{mn}>0$, $U^n_{mn}>U^n_{mr}$ and $U^n_{mn}>U^n_{rr}$ the customer buys new product from manufacturer, if $U^n_{mr}>0$, $U^n_{mr}>U^n_{mn}$ and $U^n_{mr}>U^n_{rr}$ the customer buys remanufactured product from manufacturer, otherwise buys remanufactured product from remanufacturer if $U^n_{rr}>0$. For replacement customers, if they choose the manufacturer, they get a utility $U^r_{mn}=\theta-p_{mn}+p_{mo}+s$ from the new product and a utility $U^r_{mr}=\delta_m\theta-p_{mr}+p_{mo}+s$ from the remanufactured product, however they get utility $U^r_{rr}=\delta_r\theta-p_{mr}+p_{mo}+s$ of purchasing remanufactured products from remanufacturer. If $U^r_{mn}>\delta_o\theta$, $U^r_{mn}>U^r_{mr}$ and $U^r_{mn}>U^r_{rr}$ the customer buys new product from manufacturer, if $U^r_{mr}>\delta_o\theta$, $U^r_{mr}>U^r_{mn}$ and $U^r_{mr}>U^r_{rr}$ the customer buys remanufactured product from manufacturer, otherwise buys remanufactured product from remanufacturer if $U^r_{rr}>\delta_o\theta$.

The target of the manufacturer and remanufacturer are to maximize total profits, and the Model R can be expressed as:

$$\begin{aligned}\max\pi_M=&(p_{mn}-c_{mn})(Q^n_{mn}+Q^r_{mn})+(p_{mr}-c_{mr})(Q^n_{mr}+Q^r_{mr})\\&(p_{mo}-v)(Q^r_{mn}+Q^r_{mr}))\end{aligned}$$

$$\text{s.t.}\begin{cases}Q^n_{mn}>0\\Q^n_{mr}>0\\Q^r_{mn}>0\\Q^r_{mr}>0\end{cases}\tag{2}$$

$$\max\pi_{RM}=(p_{rr}-c_{rr}-e_{rr}t)(Q^n_{rr}+Q^r_{rr})-(p_{ro}-v)Q^r_{rr}$$

$$\text{s.t.}\begin{cases}Q^n_{rr}\\Q^r_{rr}\end{cases}\tag{3}$$

As function (1), $(p_{mn}-c_{mn})(Q^n_{mn}+Q^r_{mn})$ and $(p_{mr}-c_{mr})$ $(Q^n_{mr}+Q^r_{mr})$ represent the profits from selling new products and remanufactured products respectively, and $p_{mo}(Q^r_{mn}+Q^r_{mr})$ is the total cost of trade-in in function (2). The constraint that new products and remanufactured products are both purchased by new and replacement customers. In function (3), $(p_{rr}-c_{rr})(Q_{rr}^n+Q_{rr}^r)$ represents the profits of remanufacturer, and $p_{ro}Q_{rr}^r$ is the total cost of TOR for remanufacturer. We provide the manufacturer's optimal pricing and production policy in Proposition 2.

Proposition 2. When $Q_{mr}^{n*}>0$ and $Q_{mr}^{r*}>0$, the demand constraints of manufacturer are established. The manufacturer's optimal pricing and production policy can be described as follows:

① The manufacturer's pricing policy is $p_{mn}^*=\frac{(2\delta_m-\delta_r)c_{mn}+\delta_m c_{rr}+2\delta_m-\delta_m\delta_r-\delta_r}{2(2\delta_m-\delta_r)}$, $p_{mr}^*=\frac{(2\delta_m-\delta_r)c_{mr}+\delta_m c_{rr}+2\delta_m^2-2\delta_m\delta_r}{2(2\delta_m-\delta_r)}$ and $p_{mo}^*=\frac{-c_{rr}(\delta_o\delta_m-\delta_o\delta_r)-v(4\delta_o\delta_m-2\delta_o\delta_r-6\delta_m^2-5\delta_m\delta_r-\delta_r^2)+s(2\delta_m-\delta_r)(\delta_m-\delta_r)-2\delta_o(\delta_m-\delta_r)^2}{2(2\delta_o\delta_m-\delta_o\delta_r-4\delta_m^2+4\delta_m\delta_r-\delta_r^2)}$.

② The manufacturer's production policy is $Q_{mn}^{n*}=\alpha(\frac{c_{mn}-c_{mr}+\delta_m-1}{2\delta_m-2})$, $Q_{mr}^{n*}=\alpha(\frac{2(\delta_m^2-\delta_m\delta_r)c_{mn}+(\delta_m\delta_r-2\delta_m+\delta_r)c_{mr}+(\delta_m-\delta_m^2)c_{rr}}{4\delta_m(\delta_m-\delta_r)(1-\delta_m)})$, $Q_{mn}^{r*}=(1-\alpha)(\frac{c_{mn}-c_{mr}+\delta_m-1}{2\delta_m-2})$ and $Q_{mr}^{r*}=(1-\alpha)(\frac{\delta_m-c_{mn}+c_{mr}-1}{-2+2\delta_m}+\frac{2\delta_m^2+(-v-s+2c_{mr}-c_{rr}-2\delta_r-2\delta_o)\delta_m+(v+s-c_{mr}+2\delta_o)\delta_r-(c_{mr}-c_{rr})\delta_o}{4(\delta_m-\delta_r)(\delta_0-\delta_m)})$.

Proposition 2 describes the manufacturer's optimal price and production decision under the condition that the remanufacturer provides TOR program competition. When the value of the trade in products and government subsidy are fixed, the optimal strategies of manufacturer are affected not only by the cost of its products, customer expectations and the residual value of the products, but also by the cost and customers' preference coefficient of the remanufacturer's products. With the competition of the remanufacturer, Proposition 2 indicates that the pricing decision of manufacturer is affected by the cost of remanufacturer's product, while the price of the manufacturer's product becomes more sensitive to the consumer willingness coefficient for different products. We can observe that the price of new products and remanufactured products of the manufacturer increase with the increase of the cost of the product itself and the cost of remanufacturer's product, while the trade in rebate decreases with the price of remanufacturer's product. According to Proposition 2, the new customers' and replacement customers' purchase intentions are closely related to the customer's preference coefficient for different products. Comparing Proposition 1 and Proposition 2, it is clear that the demand of new customers for new products and the number of replacement customers joining the TON program are the same, while the demand for the manufacturer's TOR demand is affected by the coefficient of consumer willingness to purchase different products due to the competition of the remanufacturer.

3.5 TON and TOR programs with remanufacturer competition and carbon tax (Model C)

This part considers the impacts of remanufacturer competition and carbon tax on the optimal strategies of manufacturer. In model C, the remanufacturer will offer TOR, whose remanufactured products compete with the remanufactured products provided by the manufacturer. The government imposes a carbon tax on carbon emissions generated by the production activities of manufacturers and remanufacturers. Consumers make purchasing decisions based on the utility of products, and the subdivision of consumers' purchase choices is the same as that in Model R.

Similar to the Model R, the optimal strategy of remanufactur and remanufacturer in Model C can be expressed as

$$\max \pi_M=(p_{mn}-c_{mn}-e_{mn}t)(Q_{mn}^n+Q_{mn}^r)+(p_{mr}-c_{mr}-e_{mr}t)(Q_{mr}^n+ -(p_{mo}-v)(Q_{mn}^r+Q_{mr}^r)$$
$$\text{s.t.}\begin{cases} Q_{mn}^n>0,\\ Q_{mr}^n>0,\\ Q_{mn}^r>0,\\ Q_{mr}^r>0; \end{cases} \tag{4}$$

$$\max \pi_{RM}=(p_{rr}-c_{rr}-e_{rr}t)(Q_{rr}^n+Q_{rr}^r)-(p_{ro}-v)Q_{rr}^r$$
$$\text{s.t.}\begin{cases} Q_{rr}^n\\ Q_{rr}^r \end{cases} \tag{5}$$

The total carbon emissions can be expressed as:

$$\min C(E)=e_{mn}t(Q_{mn}^n+Q_{mn}^r)+e_{mr}t(Q_{mr}^n+Q_{mr}^r)+e_{rr}t(Q_{rr}^n+Q_{rr}^r)$$
$$\text{s.t.}\begin{cases} Q_{mn}^n>0\\ Q_{mr}^n>0\\ Q_{mn}^r>0\\ Q_{mr}^r>0\\ Q_{rr}^n>0\\ Q_{rr}^r>0. \end{cases} \tag{6}$$

In this function (5), $(p_{mn}-c_{mn}-e_{mn}t)(Q_{mn}^n+Q_{mn}^r)$ and $(p_{mr}-c_{mr}-e_{mr}t)(Q_{mr}^n+Q_{mr}^r)$ represent the manufacturer's profits after deducting carbon emission cost, which is from selling new products and remanufactured products. In function (6), remanufacturer should pay the $e_{rr}t$ carbon emission cost. The constraints of model C ensure the demands of new and replacement customers, that both types of customers have purchased each product. We provide the manufacturer's optimal pricing and production policy in Proposition 3.

Proposition 3. When $Q_{mr}^{n*}>0$ and $Q_{mr}^{r*}>0$, the demand constraints of the manufacturer are established. Increasing the cost of carbon emissions is equivalent to increasing the total cost, so to facilitate our discussion, we define $c_{mn}+e_{mn}=c_{mne}$, $c_{mr}+e_{mr}=c_{mre}$ and $c_{rr}+e_{rr}=c_{rre}$.The manufacturer's optimal pricing and production policy can be described as follows:

① The manufacturer's pricing policy is $p_{mn}^*=\frac{(2\delta_m-\delta_r)c_{mne}+\delta_m c_{rre}+2\delta_m-\delta_m\delta_r-\delta_r}{2(2\delta_m-\delta_r)}$, $p_{mr}^*=\frac{(2\delta_m-\delta_r)c_{mre}+\delta_m c_{rre}+2\delta_m^2-2\delta_m\delta_r}{2(2\delta_m-\delta_r)}$ and $p_{mo}^*=\frac{-c_{rre}(\delta_o\delta_m-\delta_o\delta_r)-v(4\delta_o\delta_m-2\delta_o\delta_r-6\delta_m^2+5\delta_m\delta_r-\delta_r^2)+s(2\delta_m-\delta_r)(\delta_m-\delta_r)-2\delta_o(\delta_m-\delta_r)^2}{2(2\delta_o\delta_m-\delta_o\delta_r-4\delta_m^2+4\delta_m\delta_r-\delta_r^2)}$.

② The manufacturer's production policy is $Q_{mn}^{n*}=\alpha(\frac{c_{mne}-c_{mre}+\delta_m-1}{2\delta_m-2})$, $Q_{mr}^{n*}=\alpha(\frac{2(\delta_m^2-\delta_m\delta_r)c_{mne}+(\delta_m\delta_r-2\delta_m+\delta_r)c_{mre}+(\delta_m-\delta_m^2)c_{rre}}{4\delta_m(\delta_m-\delta_r)(1-\delta_m)})$, $Q_{mn}^{r*}=(1-\alpha)(\frac{c_{mne}-c_{mre}+\delta_m-1}{2\delta_m-2})$ and $Q_{mr}^{r*}=(1-\alpha)(\frac{\delta_m-c_{mne}+c_{mre}-1}{-2+2\delta_m}+\frac{2\delta_m^2+(-v-s+2c_{mre}-c_{rre}-2\delta_r-2\delta_o)\delta_m+(v+s-c_{mre}+2\delta_o)\delta_r-(c_{mre}-c_{rre})\delta_o}{4(\delta_m-\delta_r)(\delta_0-\delta_m)})$.

Technically, Proposition 3 is implied by Proposition 2, and therefore, their optimal solutions have a similar structure. In fact, the carbon tax is based on cost incentives to limit carbon emissions, which correspond to increasing the carbon emission cost on the original production cost. However, Proposition 3 helps us better understand the optimal price and production decisions of manufacturer facing the competition of

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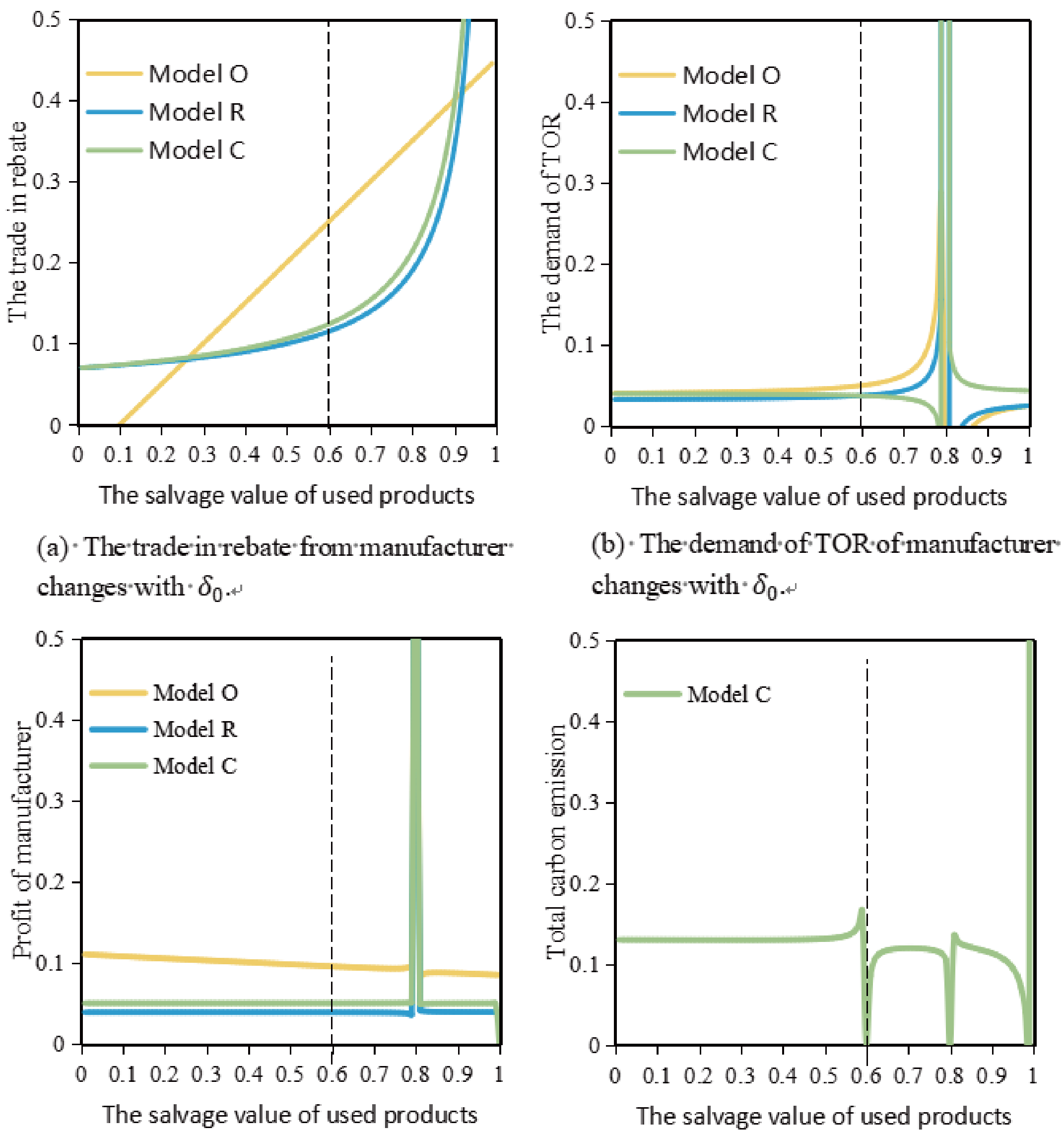
remanufactured under the constraint of carbon tax. This indicates that emission efficiency is an important factor in determining price and production strategies when carbon regulations are introduced. Under the influence of the carbon tax policy, Proposition 3 shows that the prices of new products and remanufactured products of manufacturers are affected by the carbon emission rate. At the same time, the trade in rebate provided by the manufacturer is also affected by the carbon emission rate. It's in line with Proposition 1 that the price of manufacturer's products is related to its cost. Compared with Proposition 2, we find that the introduction of carbon emission cost changes the demand for TON and TOR programs by increasing the total cost. As stated in Proposition 3, it can be seen from the demand constraints that the introduction of carbon tax has changed the power of manufacturers and remanufacturers to implement TOR program.

4 Numerical examples

In the previous section, the optimal strategies for the manufacturer to implement TON and TOR in three models are analyzed. However, due to the complexity of optimal solutions, this paper further conducts numerical research to complement aforementioned analysis and offers managerial insights. We assume that the remanufacturer has more professional remanufacturing technology, and can achieve less remanufacturing costs and carbon emissions. Referring to the previous literature, we set constant values: c_{mn} = 0.45, c_{mr} = 0.25, c_{rr} = 0.2, e_{mn} = 0.45, e_{mr} = 0.25, e_{rr} = 0.2, v = 0.1, s = 0.2, and α = 0.9, which are consistent with the settings of Refs. [7, 11, 17]. To explore the impact of residual value, remanufactured product value, remanufacturer competition and carbon tax on the implementation of TON and TOR decisions by the manu-



(a) The trade in rebate from manufacturer changes with δ_0.

(b) The demand of TOR of manufacturer changes with δ_0.

(c) The profit of manufacturer and the total carbon emission changes with δ_0.

Fig. 2. Impacts of the salvage value of used products on trade in rebate, demand of TOR, profits, and carbon emissions.

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facturer, and to analyze the profit of manufacturer and the carbon emissions of the supply chain, the variables δ_o, δ_m, δ_r, and t are changeable.

4.1 The salvage value of the used products

Fig. 2 assumes that δ_m = 0.8, δ_r = 0.6, and t = 0.3. In the three models—namely, Model O (Manufacturer with TON and TOR), Model R (TON and TOR programs with remanufacturer competition) and Model C (TON and TOR programs with remanufacturer competition and carbon tax)-the impacts of the salvage value of used products on price, demand of TON and TOR, profits, and carbon emissions are explored. To establish the demand constraints of model O, model R and model C, we set the interval of the salvage value of the used products as $0 \le \delta_o \le 0.6$.

Fig. 2a shows that the trade in rebate from manufacturer always increases with a rise in salvage value of the used products in the three models. The trade in rebate curve increases more with the residual value in Model O, and little in Model R and Model C. Clearly, with the competition of the remanufacturer, the trade in rebate is affected by more factors. Furthermore, according to the previous propositions, the salvage value of the used products have no influence on the price of new and remanufactured products from manufacturer. This indicates that manufacturer's price scheme will not be affected by the salvage value of the existing products.

Fig. 2b shows that the demand of TOR program have a small range increases with a rise in salvage value of the used products in Model O and Model R. The reason is that the demand of TOR is indirectly affected by the trade in rebate from the manufacturer. That is, according to Fig. 2a, the trade in rebate increases with a rise in the residual value, which increases the utility of the customer's purchase and the demand. However, the demand of TOR slightly decreases with a rise in large salvage value of the used products in Model C, when the salvage value of the used products is relatively large. The implementation of carbon emission cost has increased the price of remanufactured product, which negatively affects customer's utility and demand. According to the previous propositions, the salvage value of the used products has no influence on the demand of TON.

In Fig. 2c, the manufacturer's profit decreases with a rise in salvage value of the used products in Model O. Clearly, it is likely that an increase in salvage value will boost trade in rebate from manufacturer, which results in decreased profit the of manufacturer. However, in Model R and Model C, the manufacturer's profit little changes in salvage value of the used products, and is less than the profit of Model O. Due to remanufacturer competition, the total demand of manufacturers has reduced. Additionally, it can be seen from the Fig. 2c that the total carbon emissions have little change in salvage value of the used products. This indicates that the residual value has little impact on the carbon emissions generated by the supply chain when the remanufacturer also offers TOR program.

4.2 Customer's preference coefficient for remanufactured products from manufacturer

Fig. 3 assumes that δ_0 = 0.2, δ_r = 0.6, and t = 0.3.In the three models—namely, Model O (manufacturer with TON and TOR), Model R (TON and TOR programs with remanufacturer competition), Model C (TON and TOR programs with remanufacturer competition and carbon tax)—the impacts of the customer's preference coefficient for remanufactured products from the manufacturer on price, demand of TON and TOR, profits, and carbon emissions are explored. To establish the demand constraints of model O, model R and model C, we set the interval of customer's preference coefficient for the remanufactured products from manufacturer as $0.69 \le \delta_m \le 0.8$.

Fig. 3a shows that the price of new products from the manufacturer is not affected by customer's preference coefficient for remanufactured products from manufacturer in Model O, while it increases with a rise in customer's preference coefficient for remanufactured products from manufacturer in Model R and Model C. The reason is that the competition of remanufacturer has led to changes in demand, and further led to changes in price. According to Fig. 3a, the price of remanufactured product from the manufacturer increases with a rise in customer's preference coefficient for remanufactured products from manufacturer in three models. The larger the customer preference coefficient is, the greater the utility that the manufacturer obtains from purchasing products, and the manufacturer will raise the price to obtain a higher profit. When customer's preference coefficient for remanufactured products from manufacturer is fixed, the price of new and remanufactured products of manufacturer in Model O is higher than that in Model R and Model C, which is due to that manufacturers deprecate prices to increase demand with the competition of remanufacturer. Furthermore, Fig. 3a shows that, customer's preference coefficient for remanufactured products from manufacturer has no effect on the trade in rebate from manufacturer in Model O, while that have a negative effect on the trade in rebate from manufacturer in Model R and Model C. This indicates that the introduction of manufacturer competition makes the trade in rebate affected by more factors.

Fig. 3b shows that the demand of TON program decreases with customer's preference coefficient for remanufactured products from the manufacturer in three models. Additionally, it can be seen that the demand of TON in Model O and Model R is same and more than that in Model C, which indicates that the provision of TOR program by the remanufacturer has little impact on the TON program of the manufacturer, while the cost of products has a negative impact on the demand of TON. Fig. 3b shows that the demand of TOR program increases with a rise in customer's preference coefficient for remanufactured products from the manufacturer in three models. However, without a carbon tax policy, the demand of TOR program in Model C is more than that in Model R. The reason is that the introduction of carbon emission cost results in more cost advantage in remanufacturing.

In Fig. 3c, the manufacturer's profit increases with a rise in customer's preference coefficient for remanufactured products from the manufacturer in three models. Additionally, it can be seen that the profit of manufacturer in Model O is greater than that in Model R and Model C, which is because of the competition from remanufacturer. Fig. 3c shows that

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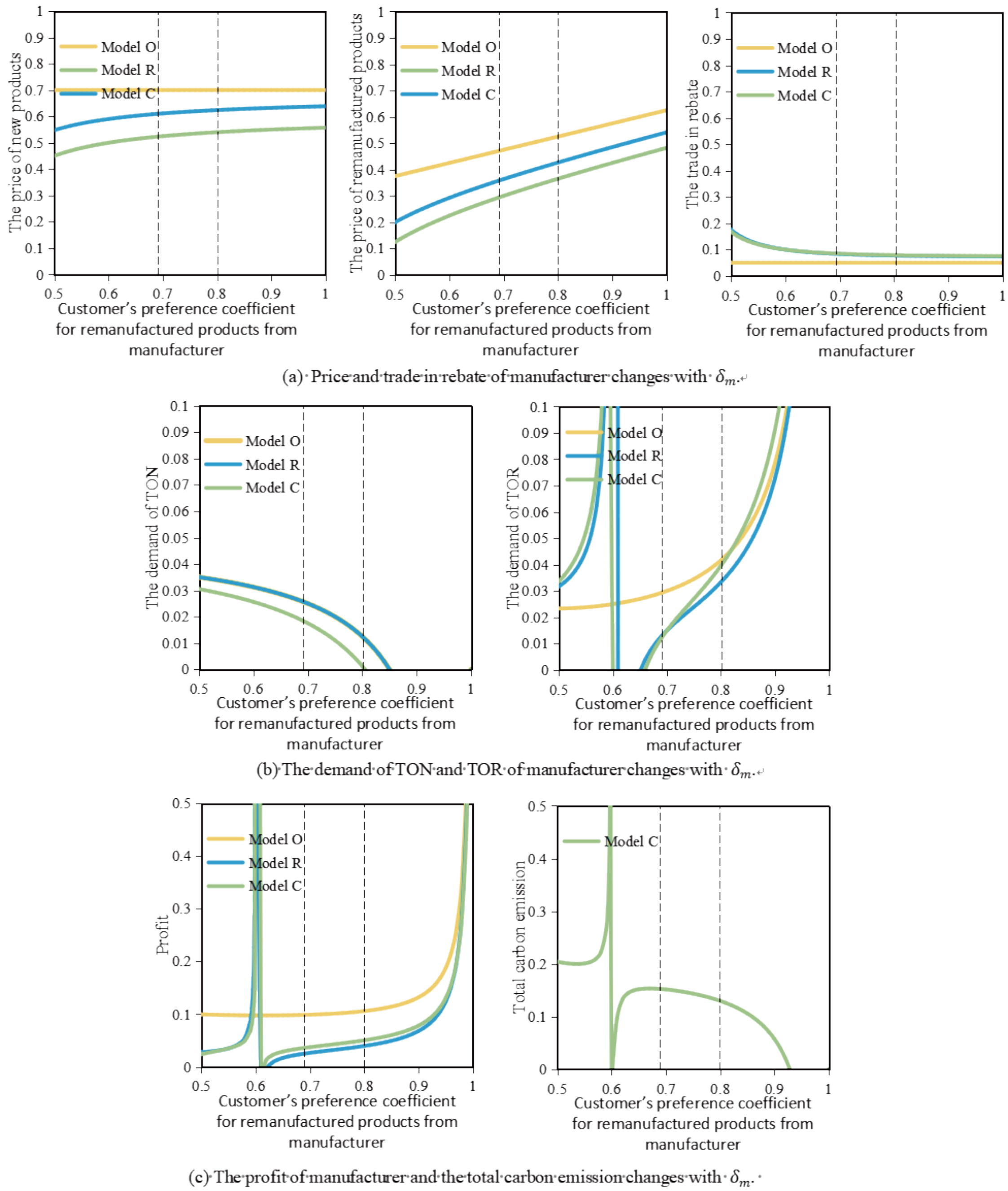


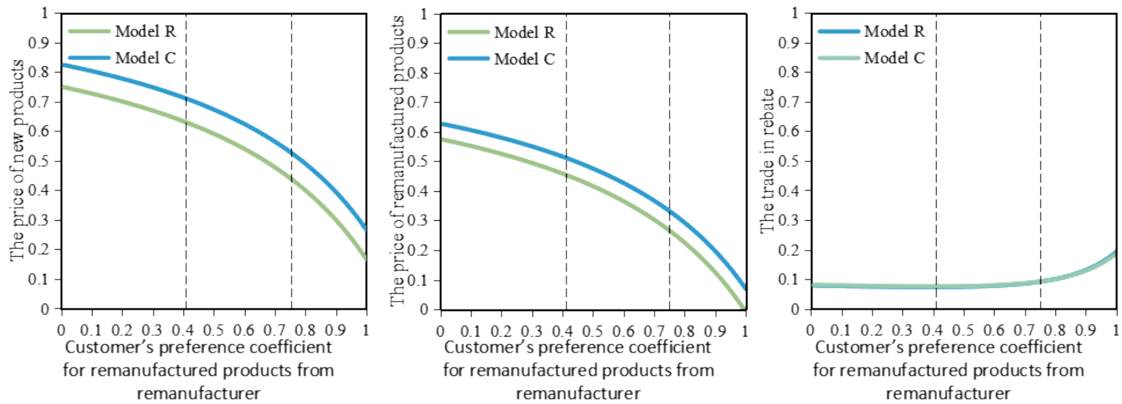
Fig. 3. Impacts of customer's preference coefficient for remanufactured products from manufacturer on price, demand, profit and carbon emission.

the total carbon emission decrease with customer's preference coefficient for remanufactured products from manufacturer. When customer's preference coefficient for remanufactured products from manufacturer increase, more customers participate in the purchase of remanufactured products, and the carbon emissions generated in the remanufacturing are lower, thus, the total carbon emissions decrease.

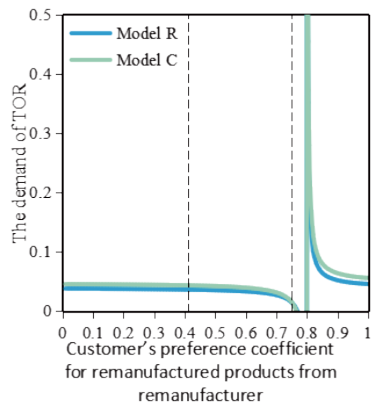
4.3 Customer's preference coefficient for remanufactured products from remanufacturer

It is assumed that $\delta_0 = 0.2$, $\delta_m = 0.8$, and $t = 0.3$ in Fig. 4, which illustrates that the impacts of the customer's preference coefficient for remanufactured products from remanufacturer on price, demand of TON and TOR, profits, and carbon emission in Model R and Model C. The new products and remanufactured products are both purchased by new and replacement customers, which denotes that the customer's preference coefficient for remanufactured products from remanufacturer satisfies $0.41 \le \delta_r \le 0.75$.

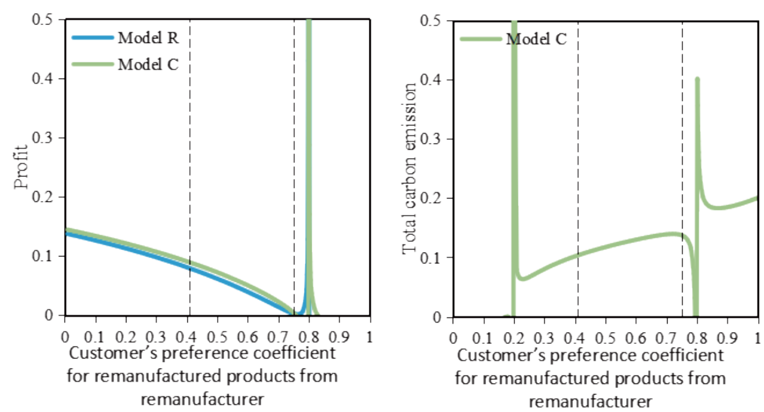
Fig. 4a shows that the price of new and remanufactured products from manufacturer decrease with customer's preference coefficient for remanufactured products from the remanufacturer in Model R and Model C. The reason is that facing the market competitiveness of remanufactured products of remanufacturers increases with customers' preference coefficient, the manufacturer will reduce prices to increase the de-



(a) Price and trade in rebate of manufacturer changes with δ_r.



(b) The demand of TOR of manufacturer changes with δ_r.



(c) The profit of manufacturer and the total carbon emission changes with δ_r.

Fig. 4. Impacts of customer's preference coefficient for remanufactured products from remanufacturer on price, demand, profit and carbon emission.

mand. Futhemore, the price of new and remanufactured products of manufacturer in Model C is more than that in Model R. This can be explained by the fact that to ensure profits, the manufacturers will raise their prices when costs increase. Fig. 3a shows that the trade in rebate increase in customer's preference coefficient for remanufactured products from remanufacturer in Model R and Model C. Obviously, the larger the customer's preference coefficient for remanufactured products from remanufacturer, the greater the market competitiveness of the remanufacturer. Therefore, the manufacturer can provide a large rebate to increase the customers utility.

Fig. 4b shows that the demand of TOR program decreases with a rise in customer's preference coefficient for remanufactured products from remanufacturer in Model R and Model C. The reason is that the increase of the customer's preference coefficient leads to an increase in the demand for remanufactured products from the remanufacturer. In Fig. 4b, the demand of TOR less than that of Model C, which is because of the introduction of carbon emission costs increases the cost advantage of remanufacturing. According to the previous propositions, the customer's preference coefficient for remanufactured products from remanufacturer have no effect on the demand of TON. This indicates that the TON decision of

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manufacturer is relatively independent of the customer's preference coefficient for remanufactured products from the remanufacturer.

Fig. 4c illustrates that the manufacturer's profit decreases with customer's preference coefficient for remanufactured products from the remanufacturer in Model R and Model C. Clearly, according to Fig. 4a and Fig. 4b, the price and demand of manufacturer mostly decrease with a rise in customer's preference coefficient for remanufactured products from the remanufacturer, which results in less profit of the manufacturer. It can be seen from the Fig. 4c that the total carbon emission increase with a rise in customer's preference coefficient for remanufactured products from the remanufacturer. This is because the carbon emissions increased by the increase of remanufacturer's production are greater than the carbon emissions reduced by the reduction of manufacturer's production, thus increasing the total carbon emissions.

4.4 Carbon tax rate

In Fig. 5, we assume that $\delta_0 = 0.2$, $\delta_m = 0.8$, $\delta_0 = 0.6$ and provide a numerical example to illustrate the impacts of carbon emission rate on price, demand of TON and TOR, profits, and carbon emissions in Model C. To establish the demand constraints of Model C, we set the interval of the carbon emission rte as $t \le 0.33$.

Fig. 5a shows that, with a rise in carbon tax rate, the price of new and remanufactured products from manufacturer will both increase, and the price of new products is greater than that of remanufactured products. The reason is that a rise in the carbon emission cost leads to an increase in the total cost of the manufacturer; however, the cost advantage of remanufactured products is more significant compared with new

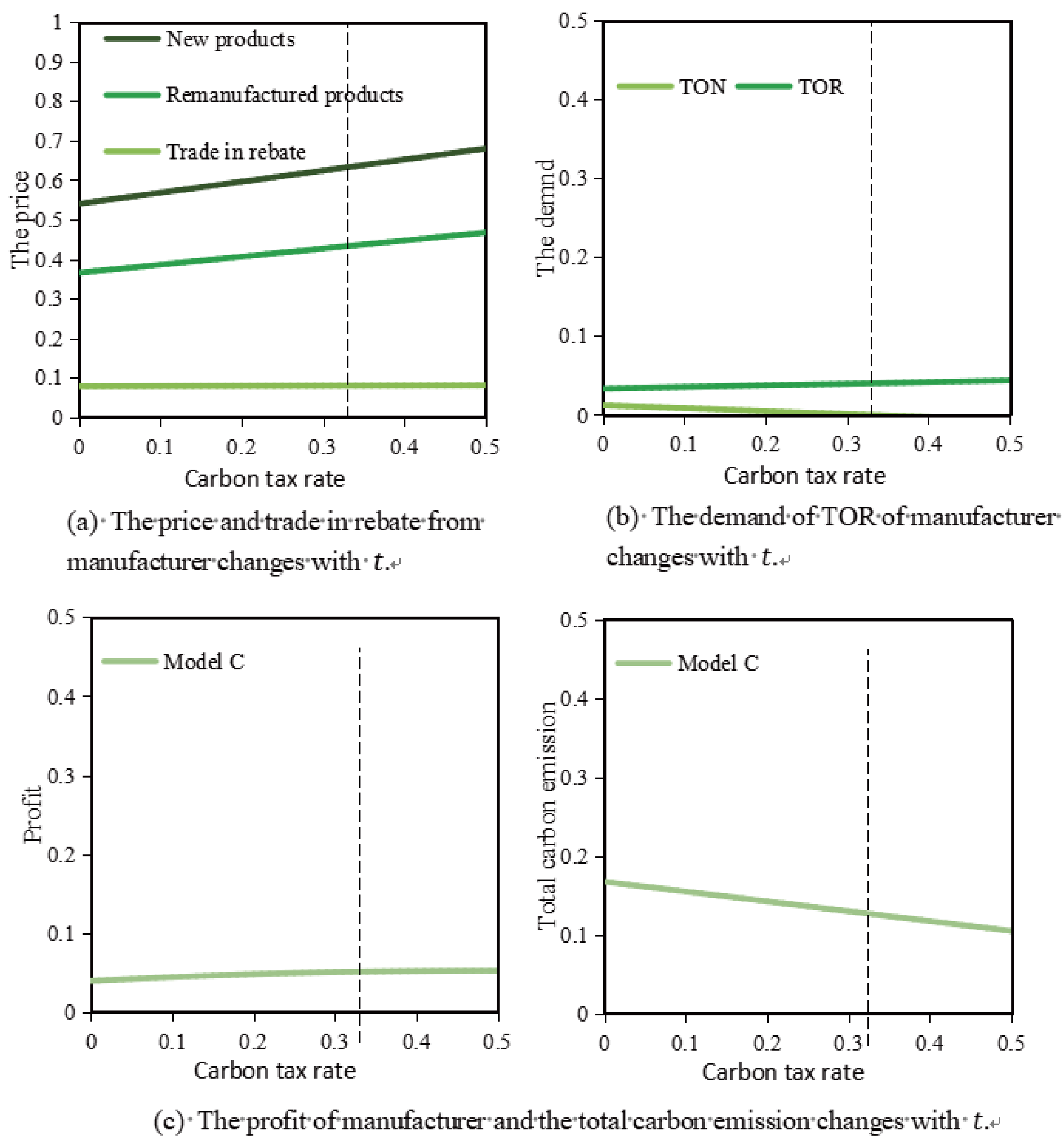

Fig. 5. Impacts of the carbon tax rate on price, trade in rebate, demand of TON and TOR, profit, and carbon emissions.

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products. Fig. 4a also shows that the trade in rebate slightly increase with carbon emission rate in Model C.

In Fig. 5b, with a rise in carbon tax rate, the demand of TOR slightly increase, while the demand of TON decrease in model C. According to Fig. 5a, the prices of new products and remanufactured products will both increase with the increase of carbon emission costs, but remanufactured products have more significant price advantages, thus the demand of new products decrease and the demand of remanufactured products increase.

Fig. 5c illustrates that the manufacturer's profit increases with a rise in carbon emission rate in Model C. This is mainly due to the cost and price advantages of remanufactured products, which bring about an increase in TOR demand. This shows that a higher carbon tax rate does not always result in manufacturer losing its profit, which provides a new insight for government and manufacturer. For governments, they should set an appropriate carbon tax rate to encourage manufacturer to reduce emissions. For manufacturers, they should improve the green technology and reduce the carbon emissions. Recall that the introduction of the carbon regulations is to limit the carbon emissions of the supply chain. In Fig. 5, the emissions curve depicts the changes of the carbon emissions with the raise of the tax rate, which shows that the total carbon emission decrease with a rise in carbon emission rate in Model C.

5 Conclusions

Considering the increasingly serious environmental problems, the carbon tax policy plays a vital role in restraining the carbon emissions of products in the manufacturing process. TON and TOR programs, as effective recycling and remanufacturing methods, are gradually and widely offered by manufacturers, and actively recommended and subsidized by the government. In addition, the competition of manufacturers is also a point worthy of attention in TON and TOR issues. As a result, our research considers the optimal strategies for manufacturer to offer TON and TOR under the competition of remanufacturers offering TOR program. Furthermore, introducing carbon tax policy to explore the impact of carbon tax on manufacturers in the competitive environment. This paper studies the manufacturers' TON and TOR schemes under the remanufacturer competition and carbon tax policy, through establishing three models: Model O (Manufacturer with TON and TOR), Model R (TON and TOR programs with remanufacturer competition) and Model C (TON and TOR programs with remanufacturer competition and carbon tax), and analyzing the impact of residual value, consumers' willingness coefficient and carbon tax policy on manufacturers and total carbon emissions through numerical experiments. Our main findings are as follows:

(Ⅰ) When constraint conditions are satisfied, the manufacturer provides TON and TOR. Under remanufacturer competition and carbon tax, the optimal price and production decision are affected by many factors, including consumers willingness to different products and carbon tax rate.

(Ⅱ) Under remanufacturer competition, a fall in consumers willingness to manufacturer's remanufactured product and a rise in consumers willingness to remanufacturer's remanufactured product will decrease the prices of manufacturer's new products and remanufactured products; a rise in residual value, a fall in consumers willingness to manufacturer's remanufactured product and a rise in consumers willingness to remanufacturer's remanufactured product will increase the manufacturer's trade in rebate.

(Ⅲ) Under remanufacturer competition, a fall in consumers willingness to manufacturer's remanufactured products will increase the demand of TON; an appropriate residual value, a rise in consumers willingness to manufacturer' s remanufactured product and a fall in consumers willingness to remanufacturer's remanufactured product will promote manufacturers to offer TOR.

(Ⅳ) Under remanufacturer competition, a fall in residual value, a rise in consumers willingness to manufacturer's remanufactured products and a fall in consumers willingness to remanufacturer's products will increase the profits of the manufacturer.

(Ⅴ) Under the carbon tax policy, the carbon tax is conducive to reducing carbon emissions. Our numerical example shows that when facing competition from remanufacturers, an appropriate increase in carbon tax rate will not reduce the profits of manufacturer, which is mainly due to the cost and price advantages of remanufacturing. Therefore, for manufacturers, they should constantly improve the remanufacturing green technology and increase market competitiveness.

Our article creatively studies the coexistence of TON and TOR under the competitive environment and carbon tax, and obtains some new findings. However, there are still some problems that have not been considered and can be studied in the future. Firstly, our paper assumes that the quality of recycled products is the same, thus the impact of quality differences on TON and TOR can be further studied in the future. Secondly, future research can consider the problem under dynamic conditions, that is, the production in the first period will affect the trade-in in the second period. In addition, our paper sets that, the manufacturer has a brand effect, and remanufacturer has cost advantage and emission advantage. In the future, we can analyze the impact of difference costs and emissions, and further consider authorized remanufacturers. Finally, this paper does not consider the issue of recycling channels in the supply chain, which can be expanded to multiple manufacturers and retailers in the future.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Yu Dong is an Associate Professor at the University of Science and Technology of China (USTC) and a Vice President of Anhui University of Science & Technology. He received his Ph.D. degree in Management from USTC. His research mainly focuses on decision science and opera-

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Appendix

Proof of Proposition 1.

When $Q_{mr}^{n*}>0$ and $Q_{mr}^{r*}>0$:

$$Q_{mn}^{n}=\alpha(1-\frac{p_{mn}-p_{mr}}{1-\delta_m}),\ Q_{mr}^{n}=\alpha(\frac{p_{mn}-p_{mr}}{1-\delta_m}-\frac{p_{mr}}{\delta_m}),$$

$$Q_{mn}^{r}=(1-\alpha)(1-\frac{p_{mn}-p_{mr}}{1-\delta_m}),\ Q_{mr}^{r}=(1-\alpha)(\frac{p_{mn}-p_{mr}}{1-\delta_m}-\frac{p_{mr}-p_{mo}-s}{\delta_m-\delta_o}).$$

Substituting them into the profit function and taking derivatives, we have $\frac{\mathrm{d}\pi_M}{\mathrm{d}p_{mn}}$, $\frac{\mathrm{d}\pi_M}{\mathrm{d}p_{mr}}$, $\frac{\mathrm{d}\pi_M}{\mathrm{d}p_{mo}}$.

Setting $\frac{\mathrm{d}\pi_M}{\mathrm{d}p_{mn}}=0$, $\frac{\mathrm{d}\pi_M}{\mathrm{d}p_{mr}}=0$, and $\frac{\mathrm{d}\pi_M}{\mathrm{d}p_{mo}}=0$, solving these three equations, we can obtain the optimal price strategies of the manufacturer as follows:

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$p_{mn}^* = \frac{1+c_{mn}}{2}$, $p_{mr}^* = \frac{\delta_m + c_{mr}}{2}$, $p_{mo}^* = \frac{\delta_o + v + s}{2}$.

Substitute the optimal prices into demand function, we have

$Q_{mn}^{n*} = \alpha(1 - \frac{c_{mn} - c_{mr}}{1-\delta_m})$, $Q_{mr}^{n*} = \alpha(\frac{\delta_m c_{mn} - c_{mr}}{2\delta_m(1-\delta_m)})$, $Q_{mn}^{r*} = (\frac{1-\alpha}{2})(1 - \frac{c_{mn} - c_{mr}}{1-\delta_m})$,

$Q_{mr}^{r*} = (\frac{1-\alpha}{2})(\frac{(\delta_m - \delta_o)c_{mn} - (1-\delta_o)c_{mr} + (1-\delta_o(V+s)}{(\delta_m - \delta_o)(1-\delta_m)})$.

Proof of Proposition 2.

When Q_{mr}^{n*}>0 and Q_{mr}^{r*}>0:

$Q_{mn}^{n} = \alpha(1 - \frac{p_{mn} - p_{mr}}{1-\delta_m})$, $Q_{mr}^{n} = \alpha(\frac{p_{mn} - p_{mr}}{1-\delta_m} - \frac{p_{mr} - p_{rr}}{\delta_m - \delta_r})$, $Q_{rr}^{n} = \alpha(\frac{p_{mn} - p_{mr}}{\delta_m - \delta_r} - \frac{p_{rr}}{\delta_r})$, $Q_{mn}^{r} = (1-\alpha)(1 - \frac{p_{mn} - p_{mr}}{1-\delta_m})$, $Q_{mr}^{r} = (1-\alpha)(\frac{p_{mn} - p_{mr}}{1-\delta_m} - \frac{p_{mr} - p_{rr} - p_{mo} + p_{ro}}{\delta_m - \delta_r})$, $Q_{mr}^{r} = (1-\alpha)(\frac{p_{mr} - p_{rr} - p_{mo} + p_{ro}}{\delta_m - \delta_r} - \frac{p_{rr} - p_{ro} - s}{\delta_r - \delta_o})$.

Substituting them into the function $\max \pi_{RM}$ and taking derivatives, we have $\frac{d\pi_{RM}}{dp_{RR}}$ and $\frac{d\pi_{RM}}{dp_{RO}}$.

Setting $\frac{d\pi_{RM}}{dp_{RR}} = 0$ and $\frac{d\pi_{RM}}{dp_{RO}} = 0$, solving these two equations, we can obtain the optimal price strategies of the remanufacturer as follows:

$p_{rr}^* = \frac{\delta_m c_{rr} + \delta_r p_{mr}}{2\delta_m}$, $p_{ro}^* = \frac{(-v+s)\delta_m^2 + ((v - p_{mr} + p_{mo})\delta_o - (s + p_{mo})\delta_r)\delta_m + p_{mr}\delta_o\delta_r}{2\delta_m(\delta_o - \delta_m)}$.

Substituting them into the profit function and taking derivatives, we have $\frac{d\pi_M}{dp_{mn}}$, $\frac{d\pi_M}{dp_{mr}}$, and $\frac{d\pi_M}{dp_{mo}}$.

Setting $\frac{d\pi_M}{dp_{mn}} = 0$, $\frac{d\pi_M}{dp_{mr}} = 0$, and $\frac{d\pi_M}{dp_{mo}} = 0$, solving these three equations, we can obtain the optimal price strategies of the manufacturer as follows:

$p_{mn}^* = \frac{(2\delta_m - \delta_r)c_{mn} + \delta_m c_{rr} + 2\delta_m - \delta_m\delta_r - \delta_r}{2(2\delta_m - \delta_r)}$,

$p_{mr}^* = \frac{(2\delta_m - \delta_r)c_{mr} + \delta_m c_{rr} + 2\delta_m^2 - 2\delta_m\delta_r}{2(2\delta_m - \delta_r)}$,

$p_{mo}^* = \frac{-c_{rr}(\delta_o\delta_m - \delta_o\delta_r) - v(4\delta_o\delta_m - 2\delta_o\delta_r - 6\delta_m^2 - 5\delta_m\delta_r - \delta_r^2) + s(2\delta_m - \delta_r)(\delta_m - \delta_r) - 2\delta_o(\delta_m - \delta_r)^2}{2(2\delta_o\delta_m - \delta_o\delta_r - 4\delta_m^2 + 4\delta_m\delta_r - \delta_r^2)}$.

Substitute the optimal prices into demand function, we have

$Q_{mn}^{n*} = \alpha(\frac{c_{mn} - c_{mr} + \delta_m - 1}{2\delta_m - 2})$,

$Q_{mr}^{n*} = \alpha(\frac{2(\delta_m^2 - \delta_m\delta_r)c_{mn} + (\delta_m\delta_r - 2\delta_m + \delta_r)c_{mr} + (\delta_m - \delta_m^2)c_{rr}}{4\delta_m(\delta_m - \delta_r)(1-\delta_m)})$,

$Q_{mn}^{r*} = (1-\alpha)(\frac{c_{mn} - c_{mr} + \delta_m - 1}{2\delta_m - 2})$,

$Q_{mr}^{r*} = (1-\alpha)\left(\frac{\delta_m - c_{mn} + c_{mr} - 1}{-2 + 2\delta_m} + \frac{2\delta_m^2 + (-v - s + 2c_{mr} - c_{rr} - 2\delta_r - 2\delta_o)\delta_m + (v + s - c_{mr} + 2\delta_o)\delta_r - (c_{mr} - c_{rr})\delta_o}{4(\delta_m - \delta_r)(\delta_0 - \delta_m)}\right)$.

Proof of Proposition 3. The proof is similar to that of Proposition 2, and $c_{mn} + e_{mn} = c_{mne}$, $c_{mr} + e_{mr} = c_{mre}$, and $c_{rr} + e_{rr} = c_{rre}$.

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