OPTIMAL PRODUCTION AND EMISSION REDUCTION POLICIES FOR A REMANUFACTURING FIRM CONSIDERING DEFERRED PAYMENT STRATEGY

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Abstract. Carbon emission reduction is regarded as an effective way to protect the environment, which requires a large amount of capital. Thus, for a remanufacturing firm with limited initial capital, trade credits act as an effective financing method in supporting production and emission reductions. In this study, under the cap-and-trade and government’s subsidy policies, a joint decision on recycling, remanufacturing and emission reduction by a financially constrained remanufacturer with considering deferred payment to a third-party recycler is analyzed. On the basis, optimization models are established to derive the optimal recycling quantity, carbon reduction rate and government subsidy rate by using a backward induction. Furthermore, an analytical comparison is provided between the cases of base model, carbon abatement investment model and deferred payment model. Numerical experiment results indicate that the remanufacturer can always make use of the investment option to further decrease its carbon emissions and gain more profit. We also find that deferred payment can effectively mitigate carbon emissions only when the degree of emission efforts is more than a certain critical value, and it also plays a positive role in the third-party recycler’s revenue, especially for the case with higher initial capital. Some other managerial implications are further discussed.

1. Introduction. As sustainable development becomes increasingly important, remanufacturing has been widely concerned by a large number of researchers and practitioners because it can considerably reduce resource waste and environmental contamination (see [28]). Thus, enterprises are encouraged by a few policies and regulations that extent the producers’ responsibility to make full use of reusable materials after consumption, produce environmentally-friendly green products, and effectively stimulate the development of the remanufacturing industry (see [15]). In addition, the widely spread environmental protection concept requires a positive response from remanufacturing firms to reduce their pollutant discharge such as carbon emissions, which have become an increasingly serious problem due to the

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aggravation of the greenhouse effect (see [7]). In view of China’s carbon intensity commitment of \( \text{CO}_2 \) emission per unit of GDP in 2020 will be lessened by 40% to 50% compared with that in 2005’, both government and firms are faced with varying degrees of pressure and challenges to reduce carbon emissions. Based on this, improving energy efficiency in manufacturing becomes an inevitable trend for energy conservation, emissions reduction and sustainability, including developing smart energy-efficient production planning and scheduling model and setting reasonable energy pricing (see [4, 16]), considering energy recovery and storage in the production planning (see [3]), focusing on energy consumption modeling and energy efficiency evaluation of related facilities and equipment during production operation (see [41]), which may all lead to lowering total energy usage and total energy cost. On the other hand, some market mechanisms including compulsory carbon caps, carbon tax and carbon trading are designed to curb the industrial carbon emissions (see [31]). To be more effective, by directly investing in technology such as purchasing greener electric applications (refrigerators, electric lamps, etc.), enhancing the energy conservation of existing electrical facility related to lighting, air-conditioning, water heating; fuel switching; obtaining energy from renewable sources, carbon emissions level can also be decreased by the manufacturers (see [29]). For example, in the fashion apparel industry, H&M, the Sweden fast fashion company, has taken many methods to minimize carbon emission in its production process by adopting new technologies and meanwhile, H&M launches the green label products which are produced in a sustainable way (H&M conscious actions sustainability report 2010 and 2012). McKinsey & Company reports that USA carbon emissions can be reduced by 3 to 4.5 gig tons in 2030 using tested approaches and high-potential technologies (see [25]).

On the other hand, under carbon emission regulation policies, not only an increasing number of firms seek for the abatement investment strategy, but also the government has actively made policies of energy conservation and emission reduction, which include environmental taxes and carbon reduction subsidies. For example, Beijing has issued the ‘Method of using fund to support clean production’ to guide and support firms to implement clean production. The ‘energy conservation and emission reduction fund subsidy project’ has been carried out by Xiamen to encourage more firms to implement energy-saving and emission-reduction reconstruction.

Considering all these carbon emission policies and government incentives, manufacturing firms are encouraged to reduce carbon emissions through production technological innovation which requires a large amount of capital investment. Thus financial flow plays a significant role in managing carbon emission reduction and firms operation, as shown in Yalabik and Fairchild [33]. Actually, many small firms with short capital are limited to acquire bank financing in the real world because of their low rate of credit. According to China’s Ministry of Commerce, only 25% of medium and small-sized enterprises successfully obtained bank loans in 2015. Accordingly, sellers with advantages access to capital make use of trade credit when a small buyer suffer a stricken under a credit crunch. By using trade credit, product or service consumers are enabled to delay the payment to their suppliers for a preset credit period, either free or in exchange with some rate of interest. In china, trade credit is used as a crucial short-term financing tool, especially for non-state-owned firms. In addition to financing function, trade credit shows other advantages such as increasing sales, reducing transaction cost, and permitting more financial
flexibility than bank loans in the era of financial crisis (see [32]). In view of these advantages, trade credit has been widely practiced, especially in the supply chain dealing bulk commodities, such as agricultural products and tea trading market.

Motivated by the actual practice in the industry, this paper studies a remanufacturing system in which the remanufacturer may face with a shortage of working capital and can acquire cores from the third-party recycler by deferred payment, usually at the expense of interest during the credit period. One of our goals in this paper is to provide guidance to the companies to make better production decisions while taking advantage of carbon reduction technology under different emission regulations. Our other purpose is to effectively alleviate the issue of capital deficient and better coordinate the profits of upstream and downstream companies in a remanufacturing system. We provide a solution and acquire optimum values of the recycling quantity, carbon reduction rate and government subsidy rate for emission reduction simultaneously that can maximize the remanufacturer’s profits. According to this analysis, a comparison of the remanufacturer’s carbon emission, profit and social welfare with and without investment availability and capital constraint has been conducted under the cap-and-trade mechanism. Further analytical and numerical examples are analyzed about the impacts of various parameters on the remanufacturer’s emissions and profit. These results can be demonstrated by the empirical and practical evidence and can provide managerial insights for managers in a remanufacturing system.

The remainder of this paper is structured as follows. Section 2 makes a brief introduction to the correlational studies. Section 3 outlines the setting and the research problems in details. In Section 4, we put forward the method to solve the model. Section 5 compares the analytical results with and without carbon abatement investment and capital constraint. Afterwards, Section 6 presents the numerical examples to verify the proposed theory. Finally, we summarize the paper with some remarks in Section 7.

2. Literature review. Our paper is closely linked to three types of literature: carbon abatement investment on production, tax and subsidy by the government and the research on trade credit in finance.

2.1. Emission abatement investment. As noted, leading companies in their fields are willing to invest to decrease the environmental pollutions of production and logistics processes. In this paper, carbon abatement investment related research positioning are summarized in Table 1. However, the related studies are classified in two groups. The first group of papers study the carbon offset investments with considering a carbon-offset policy. For example, Benjaafar et al. [5] show that firms could effectively reduce their carbon emissions by making only operational adjustments and by collaborating with other members of their supply chain instead of costly investing in carbon-reducing technologies. Using the EOQ model, Chen et al. [8] provided a condition under which it can reduce emissions by modifying order quantities and the relative emission reduction is greater than the relative increase in cost. The second group of studies consider investing in technology to decrease the environmental pollutions of production and logistics processes under various emission regulations, including emission caps, taxes on emissions, and cap-and-trade. Among these papers, a few researchers explored the problem in a supply chain system, they made it clear that in order to develop sustainable supply chain, in addition to carbon reduction with considering carbon emission policies,
cleaner technology investment should also have been put forward (see [13, 35]). On the other hand, from firms’ perspective, the effects of investment decisions on the profit and carbon emissions was first analyzed by Jiang and Klabjan [17]. Toptal et al. [25] analyzed a unite decision on supplement of stocks and carbon investment for a retailer under three carbon emission regulation and policies. Luo et al. [18] found that adopting green technology investment enhanced the efficiency of emission reduction, which led to lower carbon emission per unit and a higher margin in both the perfect competition and co-operation competition. Other related works include Chen et al. [9] and Drake et al. [14]. Similar with the works above, this paper also contributes to the second group of literature. Specially, a remanufacturing firm’s joint production and carbon abatement investment decisions are mainly concerned in this paper which differs from the previous research.

### Table 1. Carbon abatement investment related research

| Research object       | Carbon abatement investment methods | Carbon emission regulation | Tax or subsidy | Consumer environmental awareness | references                      |
|-----------------------|-------------------------------------|----------------------------|----------------|---------------------------------|---------------------------------|
| Supply chain          | Offset investment                    | Cap-and-offset, carbon tax, cap-and-trade policy | No             | No                              | Benjaafar et al. (2013), Dong et al. (2010), Yang et al. (2017), Qiu and Tao (1998), Wang et al. (2018) |
|                       | Technology investment                | cap-and-trade policy       | Yes            | No                              | Yu et al. (2016)                |
| Individual firm       | Offset investment                    | Cap-and-offset, carbon tax, cap-and-trade policy | No             | Yes                             | Chen et al. (2013)              |
|                       | Technology investment                | Cap-and-trade              | No             | No                              | Chen et al. (2017), Luo et al. (2016) |
| Remanufacturing firm  | Technology investment                | Carbon cap, carbon tax, cap-and-trade policy | Yes            | Yes                             | Yalabik and Fairchild (2011)    |

#### 2.2. Tax and subsidy.
As investment decisions for environmental consideration among firms are highly encouraged by the government, some fiscal policies implemented by government to promote the emission reduction also have been into account. At present, quite a few literatures have discussed enterprises’ decisions in a low-carbon supply chain under the government intervention from different perspectives. For example, the assumption that the government subsidized the technological innovation input of firms to a certain proportion was supposed by Qiu and Tao [22]. Yu et al. [39] developed an optimization model under oligopolistic competition considering green preferences and government subsidies, with the objective of profit maximization for the manufacturers. Specially, Wang et al. [29] provided a thorough evaluation and analysis of the effects of Fund policy for subsidizing WEEE dismantling with data gathered from a total of 109 certified treatment enterprises.

#### 2.3. Trade credit.
However, the rapidly growing literature on the operation-finance interface examines the interplay between firms’ operation decisions and financial frictions. Our paper mainly focuses on reviewing researches about trade credit in the supply chain settings and firm’s operational decisions. The role of trade credit has been investigated by quite a number of studies from various aspects and the related literature positioning in this paper are summarized in Table 2. Some researches show that trade credit is a superior option compared with bank loan because it provides the retailer an incentive to win more orders than the traditional
newsvendor model. Babich and Tang [2] as well as Rui and Lai [23] indicated how trade credit could be used to mitigate a supplier’s moral hazard. Similarly, Peura et al [21] found that adopting trade credit might increase the benefits of firms who are engaged in price competition. However, in some literature, Stackelberg game theory was frequently used to solve the financing problem between the supplier and the retailer in a capital-constraint supply chain, in which the supplier is usually a profit-maximizing Stackelberg leader. For example, Tunca and Zhu [26] showed that buyer-intermediated financing could effectively improve channel performance and benefit supply chain parties simultaneously by building a game-theoretical model. Other related works include Yang and Brige [36, 37], Devalkar and Krishnan [12] as well as Chod [11]. In addition, in recent years, supply chains coordination with capital constraint was investigated by a few researchers. For example, Lee and Rhee [19] adopted the trade credit to coordinate a supply chain when both the supplier and the retailer are financially constrained. Considering bank financing and trade credit in a financially constrained supply chain, Xiao et al. [32] examined whether revenue-sharing, buyback, and all-unit quantity discount contracts can coordinate the supply chain. Similarly, Tsao [27] focused on channel coordination when a retailer provides trade credit to end customers and provided four composite contracts to induce the retailer to make decisions while optimizing the channel profit. Different from the previous researches in a supply chain environment, this paper mainly focuses on a remanufacturing system consisting of a remanufacturer and a third-party recycler, in which we conduct deferred payment financing, which can effectively solve the problem of short cash.

### Table 2. Trade credit related research

| Research object | Financing method | Supply chain coordination | Default risk | references |
|-----------------|------------------|---------------------------|--------------|------------|
| Supply chain    | Bank loan & trade credit | No | No | Chod (2016) |
|                 | No | Yes | Yes | Xiao et al. (2017), Yang and Birge (2017) |
| Trade credit    | No | No | No | Peura et al. (2017), Tunca and Zhu (2017) |
|                 | Yes | Yes | No | Babich and Tang (2012), Rui and Lai (2015) |
| Remanufacturing system | Bank loan | No | No | Tsao and Yu-Chung (2017), Lee and Rhee (2011) |
| Remanufacturing system | No | Yes | Yes | Devalkar and Krishnan (2014), Yang and Birge (2011), Li (2018), |
| Trade credit    | No | No | No | Sun et al. (2017), Wang et al. (2017), Wang and Chen (2017) |

As reviewed above, even though various important aspects in carbon reduction and operating financing have been examined by the existing literature, they are all studied separately and mainly focused on a supply chain system. In light of the research gap identified above, we develop a comprehensive model aiming to be more practical and generalize several of the aspects mentioned earlier. Specially,
a few amount of literature in our team have focused on remanufacturing production decision, which may consider carbon emissions or financial factors (see [10, 20, 24, 31, 30]). Among, Wang and Chen ([31, 30]) discussed the manufacturing/remanufacturing production and financing decisions by considering different capital conditions under carbon emission regulations, and set up three kinds of mathematical models to determine the optimal quantities and maximize the total profit, which is mostly related our paper. But differently, additional to the carbon emission regulations, we also take into account carbon abatement investment and consider the trade credit as a new financing way. However, our paper contributes to the literature in two aspects: (i) we are the first to study production and carbon abatement investment in a remanufacturing system consisting of a third party recycler and a capital-constrained remanufacturer; (ii) combined with the characteristics of remanufacturing, we consider the case of deferred financing of the remanufacturer, and compare the proposed model with the case of no capital constraint. To the best of our knowledge, none of the existing studies discussed all these important factors simultaneously. In this paper, we aim to address this shortcoming.

3. Notion and problem description. This section describes the remanufacturing system and market demand, carbon reduction and government incentives, and capital structure and financing mode underlying the basic model.

3.1. Remanufacturing system and market demand. We consider a monopolistic remanufacturer who acquires and remanufactures the obsolete products from the third-party collector in a market driving remanufacturing system and sells in the second market in which the demand is random. Each core’s quality is different and unknown before recycling. The remanufacturing process may incur losses due to either process handling problems or the unexpected problems, such as the inferior quality of recycled products. The remanufacturing rate is defined as $\xi$ (the loss rate is $1 - \xi$). The rest of the cores are disposed due to their inferior quality with a scrapping cost $c_0$. However, with limited demand information, there is a risk of overproduction or out-of-stock for the remanufacturer, which will also cause a certain loss. In this paper, it is assumed that there is complete information and information symmetry between the remanufacturer and recycler, both of them are risk-neutral. In addition, the cores’ need can be met and the fixed costs have no capacity constraint.

Figure 1 describes the remanufacturing process from recycling to sale among different parties in a remanufacturing system.

3.2. Carbon reduction and government incentives. The same as the assumption in Qiu et al. [22], the government may throw a subsidy of emission reduction for the remanufacturer with a subsidy rate $f$. Therefore, driven by this situation, the remanufacturer can reduce carbon emissions by making a one-time investment in new technology, equipment or machinery, which is similar to Yalabik and Fairchild [33]. Simultaneously, based on the cap-and-trade regulation, the remanufacturer can purchase quota from the carbon trade market if its total carbon emission surpasses the original cap, or he may exchange one unit of carbon emissions for the value of one unit of monetary. The carbon trading quotas $E_m = (1 - \tau)E_0(q) - E_g$, where $E_0(q) = e_0q$ represents the initial emissions for production before investment. The cost coefficient of carbon emission reduction $m$ is assumed to be considerably large. Thus without loss of generality, the remanufacturer’s investment of carbon reduction
is \( \frac{1}{2} (1 - f) m \tau^2 \), where \( \tau \) is the mitigation rate, which is similar in literature [39]. It is noted that the emission baselines are different among different products, whereas the efficiency of carbon reduction \( \tau \) can be compared among different products. In short, both the degree of emission reduction efforts and the level of carbon trading price have an impact on its emission reduction effect.

To avoid trial solutions, the following assumptions are needed:

1. The price of carbon trading is an exogenous variable and is determined by the carbon market.
2. The investment of emission reduction is a monotone increasing function of carbon reduction rate, \( I = \frac{1}{2} (1 - f) m \tau^2 \), \( I(0) = 0 \), \( I(1) = +\infty \), \( I'(\tau) > 0 \), \( I''(\tau) > 0 \).
3. We can see from the above equation that the government subsidy rate \( 0 < f < 1 \), otherwise, the carbon abatement investment is negative.

### 3.3. Capital structure and financing mode.

As the self-owned capital by the remanufacturer is not sufficient for carbon abatement investment, the remanufacturer finances in the form of deferred payment. That is, by signing a credit contract with the third-party recycler, the recovery fund will be paid at the end of the sales period. Considering the time value of capital and credit risk, the unit recycling price in deferred payment increases with the length of the deferred payment loan \( M \), that is, \( a' = a e^{kM} \), with \( k \) a time-length sensitivity coefficient of deferred payment. Suppose the remanufacturer complies with the contract terms to avoid a debt default during the credit period, and under the trade credit contract, the third party recycler should protect the remanufacturer from default.

Table 3 summarizes the notation that will be used in this paper. Additional notation will be defined as needed.

### 4. Establishing and solving the models.

In this section, we analyze the remanufacturer’s production and carbon reduction decisions under various capital levels with and without abatement investment strategy. In each situation, the issue is to find the optimal recycling quantity, carbon reduction rate and carbon emission subsidy that jointly maximize expected profits and social welfare of the remanufacturer and the third-party recycler. Specially, we adopt the backward sequential decision-making approach to solve the above models by utilizing Stackelberg game
Table 3. Notation

| Indices | Description |
|---------|-------------|
| $i$     | Index for the case of Model $j$, $i = 1, 2, 3$ for Model I, II, III respectively. |
| $j$     | Index for model, $j = I, II, III$. |

Parameters

- $c$: Unit remanufacturing cost.
- $c_0$: Unit disposal cost.
- $h$: Unit stock-holding cost.
- $s$: Unit shortage cost.
- $v_t$: Unit acquisition price by the third-party recycler.
- $a$: Unit recycling price by the remanufacturer.
- $p$: Unit sales price, $p > s > c$.
- $\xi$: Remanufacturing rate.
- $D$: Stochastic demand with support on $[0, +\infty)$, CDF $F()$, PDF $f()$. Suppose it obey the uniform distribution on $[\alpha, \beta]$, $F(\alpha) = 0$, $F(\beta) = 1$.
- $q_i$: Production quantity for Model $j$, $q_i = R_i^* \xi$.
- $t$: Consumers’ low carbon preference coefficient.
- $\delta$: Environmental benefit coefficient.
- $c_m$: Unit carbon trading price.
- $e_0$: Initial unit carbon emissions.
- $\Delta e_i$: Unit carbon emission reduction for Model $j$.
- $m$: Cost coefficient of emission reduction.
- $E_g$: Carbon emission quota.
- $B$: Initial capital by the remanufacturer.
- $T_1, T_2$: Recycling period and production period.
- $M$: Sales period/credit period.
- $k$: Sensitivity to deferred payment length.
- $\pi_{ri}, \pi_{ti}$: The profit by the remanufacturer and the third-party recycler for Model $j$, respectively.

Decision variables

- $R_i$: Recycling quantity of Model $j$ by the remanufacturer.
- $\tau_i$: Carbon reduction rate of Model $j$, $\tau_i = \Delta e_i / e_0$.
- $f_i$: Government subsidy rate for carbon emission reduction of Model $j$.

theory, which is most suitable for two stage decision problem. Note that we present the optimal solution for each strategy $i$ with a pair of values ($R_i^*, \tau_i^*, f_i^*$).

4.1. Model: Ample cash.

4.1.1. Model I: The base case. For the sake of convenience, we firstly explore the optimal decisions and profit in this model where the remanufacturer recycles and produces used products without capital constraint and carbon abatement investment. We take a remanufacturing system into account where the third-party recycler games with the remanufacturer and place orders based on this decision: the third-party recycler firstly sets up the recycling price, and the remanufacturer determines the sales price of products later. Based on the cap-and-trade mechanism, the carbon trading quotas is $E_m = E_{01}(q) - E_g$.

We assume that each consumer will only gain satisfaction from consumption of the first unit of the product and buy one unit of product. Hence, consumer utility function $u(t)$ is represented by $u(t) = t - p$, with $t$ the low carbon preference on the remanufactured goods. If $t = 0$, consumers would consider not buying remanufacturing products. If $t = 1$, the consumers are defined as “green consumers”, who are aware of environmental protection or only care about what the product does. (see [1]).
According to the above statements and assumptions, the remanufacturer’s total profit is calculated in a case where the market demand for the remanufactured products is a random variable which obey the uniform distribution on \([\alpha, \beta]\), \(F(\alpha) = 0\) and \(F(\beta) = 1\). The profit function is as follows:

\[
\pi_r(R_1) = p \min(D, q) - aR - cq - c_0(R-q) - h \max(q-D,0) - s \max(D-q,0) - c_m[E(q) - E_g] \\
= [p\xi - a - c\xi - c_0(1 - \xi) + s\xi - c_0 c_m \xi]R - sE(x) \\
+ c_m E_g - (p + h + s) \int_0^q F(x)dx
\]

(1)

Among, \(q_1 = R_1\xi, \tau_1 = \Delta \xi / \xi_0\)

The first term on the right side of Eq. (1) defines the sales revenue. The second to forth terms define the total costs for production, including recycling and remanufacturing costs as well as the disposal cost of poor quality cores. The fifth and sixth terms represent the shortage loss and stock-holding cost in the case of over-production. And the last term represents the cost of carbon emission. Note that the optimal solution is consistent with the classical newsboy model. The detailed calculations for the optimal solution and related discussions are placed in Appendix (Proof of Theorem 1).

Thus, the third-party recycler’s profit function is as follows:

\[
\pi_t(R_1) = (a - v_t)R_1
\]

(2)

However, without abatement investment and capital constraint, our social welfare in this model consists of the firm’s profit and consumer surplus, which is defined as:

\[
s_w = t cs_1 + \pi_r + \pi_t
\]

(3)

In which, according to Yenipazarli [38], the consumer surplus in defined by

\[
tcs_1 = t \int_0^1 u(t)dt = \frac{1}{2} tp(1 + p)
\]

(4)

**Theorem 4.1.** The objective function (1) is concave. Assume that the random market demand \(D\) meets the uniform distribution on \([\alpha, \beta]\) where \(\beta > \alpha > 0\), we derive the optimal solution of \(R_1^*\).

\[
R_1^* = \left\{ \frac{(p - c + c_0 + s)\xi - a - c_0 - c_m c_0 \xi}{(p + h + s)\xi^2} \xi + \frac{(p - c + c_0 + s)\xi - a - c_0 - c_m c_0 \xi}{(p + h + s)\xi^2} \xi \right. \\
\left. + \frac{\alpha}{\xi} \right\} \frac{\varphi_1 - a}{\varphi_2 \xi^2} + \frac{\alpha}{\xi}
\]

(5)

Among, \(\varphi_1 = (p - c + c_0 + s - c_m c_0)\xi - c_0, \varphi_2 = p + h + s\)

Since the objective function is concave, solving \(\frac{\partial \pi_r}{\partial R_1} = 0\) yields the optimal recycling quantity for the remanufacturer. Proof is seen in Appendix.

**4.1.2. Model II: With carbon abatement investment.** In this model, the remanufacturer’s cost mainly comes from remanufacturing and abatement investment. The abatement investment is mainly related with the emission reduction rate \(\tau\). The actual unit of carbon emission equals to the value that the original unit carbon emission minus the carbon emission reductions, that is: \((1 - \tau_2)e_0\). Thus, in view of abatement investment, the total emission permits mainly come from three channels: the initial government quota \(E_g\), emission reduction \(\tau E(q)\) and the emission
trading volume $E_m$, that is: $E_{m2}(q) = E_g + E_{m2} + \tau_2 E_{m2}(q)$. Among which, $E_{m2} > 0$ signifies purchasing carbon emission rights and $E_{m2} < 0$ represents marketing carbon emission rights.

Thus, with carbon abatement investment in place, the total expected profit is given by:

$$
\pi_{r2}(R_2, \tau_2, f_2) = p \min(D, q) - aR - cq - c_0(R - q) - h \max(q - D, 0) - s \max(D - q, 0) - c_m[(1 - \tau)E(q) - E_g] + \delta \tau E(q) - \frac{1}{2} m(1 - f)\tau^2
$$

$$
= p \min(D, q) - aR - cq - c_0(R - q) - h \max(q - D, 0) - s \max(D - q, 0) + c_m E_g + [(\tau - 1)c_m + \delta \tau]E(q) - \frac{1}{2} m(1 - f)\tau^2
$$

$$
= [p\xi - a - c\xi - c_0(1 - \xi) + s\xi - (1 - \tau)c_0\xi c_m + \delta c_0 \xi \tau]R - sE(x) - (p + h + s) \int_0^q F(x)dx + c_m E_g - \frac{1}{2} m(1 - f)\tau^2
$$

(6)

The first to sixth terms are the same as those mentioned in Model I. The last three terms represent the cost of carbon emission, the environmental benefits and the carbon abatement investment. The detailed calculations for the optimal solution and related discussions are placed in Appendix (Proof of Lemma 1 and Theorem 2).

Thus, the third-party recycler’s profit function is given by:

$$
\pi_{t2}(R_2) = (a - v_t)R_2
$$

(7)

Compared with production planning, emission reduction inputs require longer lead time, we make the game order in two stages. As mentioned above, we use the backward induction to analyze the problems and the diagram to further declare this game model is as following (Figure 2). In the second stage, we solve the remanufacturer’s problem and obtain the optimal response of the recycling quantity ($R$) and carbon reduction rate ($\tau$) based on the subsidy rate of abatement investment given by the government ($f$). Back to the first stage, we solve for the optimal subsidy rate of abatement investment ($f^*$), given the optimal response of recycling quantity ($R^*$) and carbon reduction rate ($\tau^*$).

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**Figure 2.** Framework of the game model of Model II.
To analyze this question, we define social welfare as the sum of the consumer surplus, firm’s profit and the values that the environmental benefits of carbon reduction minus the subsidy expenditure of the government in this model. Thus, the social welfare is as follows:

$$sw_2 = tcs_2 + \pi_{r_2} + \pi_{t_2} + B_2(E) - GE_2$$  \hspace{1cm} (8)$$

In which, environmental benefits are defined with a linear function of emission reduction:

$$B_2(E) = \delta E_0 (q) \tau_2$$, with \(\delta > 0\) an index of the benefit associated to emission reduction. And the government expenditure owes to the subsidy of abatement investment:

$$GE_2 = \frac{1}{2} m f_2 \tau_2^2$$

Specially, before tackling the problem, some conditions have to be determined:

(A1) The minimum possible carbon emission as production decision exceeds the maximum possible carbon reduction because of investment decisions. That is, \(0 < \tau_2 < 1\).

An implication of assumption A1, therefore, is that the carbon emission cannot be completely eliminated with new technology.

(A2) For the cap-and-trade policy under consideration, there exists a value of \(I_2 > 0\) at which environmental benefits and carbon trading will increase when \(I\) monetary units are invested to reduce carbon emissions exceed the investing cost. That is,

$$I_2 < \delta \tau_2 E(q) + c_m E_m$$  \hspace{1cm} (9)$$

Assumption A2, in mathematical terms, is equivalent to saying that there exists some \(I > 0\) at which \(c_m \tau_2 E(q) > I_2\), which means the cap-and-trade policy, considering the measure of cost of unit emission reduction, may sometimes be profitable depending on whether the company is able to exceed carbon allowance to sell or not. If assumption (A2) does not hold, the investment to reduce the carbon emission does not pay off, thus the investment decision should not be considered.

**Lemma 4.2.** The objective function (6) is concave when it satisfies C1.

We can demonstrate that the objective function is concave, the optimization is convex, then we can conclude that it has an optimal solution, which is presented in Theorem 2 below.

**Theorem 4.3.** Assume that the random market demand \(D\) meets the uniform distribution on \([\alpha, \beta]\) where \(\beta > \alpha > 0\). When the remanufacturer is not financially constrained and investing in reducing emissions, there exists the optimal solution of \(R_2^*, \tau_2^*\) and \(f_2^*\) if it satisfies C2, which is shown as below. Specially, \(R_2^*\) and \(\tau_2^*\) depends on \(a, c\) and \(c_0\), whereas \(f_2^*\) is independent of \(a, c\) and \(c_0\).

$$R_2^* = \frac{m \varphi_2 - e_0 \delta \varphi_1 (\beta - \alpha)[(\varphi_1 - a)(\beta - \alpha) + \alpha \xi \varphi_2]}{m \varphi_2 - \varphi_1 \varphi_2 (\beta - \alpha) \xi \varphi_2^2}$$  \hspace{1cm} (10)$$

$$\tau_2^* = \frac{\phi_3 [(\varphi_1 - a)(\beta - \alpha) + \alpha \xi \varphi_2]}{m \varphi_2 - \varphi_1 \varphi_2 (\beta - \alpha) \xi}$$  \hspace{1cm} (11)$$

$$f_2^* = \frac{\delta \varphi_2^2 (\beta - \alpha) + m \varphi_2}{m \varphi_2 (c_m + 2\delta)}$$  \hspace{1cm} (12)$$

Among, \(\phi_1 = e_0 (c_m + \delta)\), \(\phi_2 = e_0 (c_m + 3\delta)\), \(\phi_3 = e_0 (c_m + 2\delta)\)

The proof is given in Appendix.
4.2. Model III: Capital constraint with carbon abatement investment. In this model, the remanufacturer will keep investing in the emission reduction and apply for deferred payment financing due to the limitation of initial cash, which is mainly for emission reduction. The game order is similar with Model II: Firstly, the third-party recycler decides the recycling price under the deferred payment strategy. Thereafter, the remanufacturer decides the amount to acquire from the recycler. Finally, at the end of the credit period, recovery funds are returned to the recycler. Considering the time value of money, after the demand of the remanufacturer has been fully realized, the third-party recycler may require the remanufacturer to repay the recycling price with a new value of \( a' = a e^{kM} (k > 0, M \geq 0) \), obviously, the new price is an increasing function of the time length of deferred payment by the remanufacturer. Figure 3 illustrates the sequence of events.

The total emission permits structure is the same as Model II: \( E_{03}(q) = E_g + E_{m3} + \tau_3 E_{03}(q) \), and the final average emission amount is given by: \( E_3(q) = (1 - \tau_3)E_{03} \).

Thus, the optimization model becomes:

\[
\pi_{r3}(R_3, \tau_3, f_3) = \min \left\{ p \min(D, q) - cq - c_0(R - q) - h \max(q - D, 0) - s \max(D - q, 0) \right\} \nonumber
\]

\[
- ae^{kM} R - c_m [(1 - \tau)E(q) - E_g] + \delta \tau E(q) - \frac{1}{2} m(1 - f) \tau^2 \nonumber
\]

\[
= p \min(D, q) - cq - c_0(R - q) - h \max(q - D, 0) - s \max(D - q, 0) \nonumber
\]

\[
- ae^{kM} R + c_m E_g + [(1 - \tau) c_m + \delta \tau] E(q) - \frac{1}{2} m(1 - f) \tau^2 \nonumber
\]

\[
= [p \xi - c_0(1 - \xi) + s \xi - (1 - \tau)c_0 \xi c_m + \delta c_0 \xi \tau - ae^{kM}] R \nonumber
\]

\[
- sE(x) - (p + h + s) \int_0^q F(x)dx + c_m E_g - \frac{1}{2} m(1 - f) \tau^2 \quad (13) \nonumber
\]

\[
s.t. \left\{ \begin{array}{l}
B \geq cq_3 + aR_3 \\
 \tau_3, R_3, f_3 > 0 \\
B \geq cq_3 + \frac{1}{2}(1 - f_3)m \tau_3^2 \end{array} \right. \quad (14) \nonumber
\]

Among, \( q_3 = R_3 \xi, \tau_3 = \Delta e_3/c_0, E_3(q) = c_0q_3 \).

In this function, constraint (14) supposes that the self-owned capital B is sufficient for recycling and production cost, and can also supports for the production and emission reduction. The detailed derivations and corresponding discussions of the optimal solution are placed in Appendix (Proof of Lemma 2, Theorem 3 and 4).
The third-party recycler’s profit function is given by:

\[ \pi_3(R_3) = (a' - v_t)R_3 \]  

(15)

Where \( a' \) is the recycling price for deferred payment, and \( a' = ae^{kM} \).

To solve the problem, we make a decision at the beginning of the production period. The same as in Model III, we make use of backward induction to derive the unique equilibrium optimal solution.

Therefore, the social welfare function becomes:

\[ sw_3 = tcs_3 + \pi_r + \pi_t + B_3(E) - GE_3 \]  

(16)

The same as Model II, to ensure the validity of Model III, it is noted that the maximum possible carbon reduction rate due to investment decisions \( 0 < \tau_3 < 1 \).

Furthermore, in view of deferred payment policy, there exists a value of \( I_3 > 0 \) in which the environmental benefits and carbon trading exceed the carbon abatement investment cost and deferred interest. That is,

\[ (a' - a)R_3 + I_3 < \delta \tau_3 E(q) + c_mE_m \]  

(17)

Compared with Model II, we find that \( I_3 \) is smaller than \( I_2 \), which means that capital constraint and financing shrinks the degree of carbon abatement investment.

**Lemma 4.4.** The objective function (13) is concave if it satisfies C1.

We can demonstrate the concavity of objective function and the convexity of constraints, thus the optimization is convex with an optimal solution. By using constraints (14) and the Karush-Kuhn-Tucker (KKT) conditions, which is a common method for solving nonlinear programming problems, we construct a Lagrange function and may obtain the optimal production and emission reduction strategies of the remanufacturer, which is summarized in Theorem 3 below.

**Theorem 4.5.** Assume that the random market demand \( D \) meets the uniform distribution on \([\alpha, \beta]\) where \( \beta > \alpha > 0 \). When the remanufacturer is financially constrained and investing in reducing emissions, there exists the optimal solution \( R_3^*, \tau_3^* \) that depends on \( B \), which is shown below.

Model III is divided into two cases according to the level of initial cash: The initial cash is sufficiently low and it is high enough. Among, we define the situation \( B < \min(B_1, B_2) \) as case 1 of Model II and the situation \( B > \max(B_2, B_3) \) as case 2 of Model III.

The proof can be seen in Appendix.

**Theorem 4.6.** When the remanufacturer is financially constrained and investing in reducing emissions, the optimal solution of \( f_3^* \) can be derived in the existence of the optimal \( R_3^* \) and \( \tau_3^* \) when it meets C2, the optimal production and emission reduction decisions under different levels of self-owned capitals are shown below. For a detailed comparison, see proposition 3.

\[
(R_3^*, \tau_3^*, f_3^*) = \begin{cases} 
(R_3^{(1)}, \tau_3^{(1)}, f_3^{(1)}) & B < \min(B_1, B_2) \\
(R_3^{(2)}, \tau_3^{(2)}, f_3^{(2)}) & B > \max(B_2, B_3) \\
\text{produce no products} & \min(B_1, B_2) < B < \max(B_2, B_3) 
\end{cases} 
\]  

(18)

It is noted that:

\[
B_1 = \frac{2am(a + c\xi)^2}{\phi_1\phi_2\xi^2}, \quad B_2 = \frac{m(1 - f)(a + c\xi)[(\phi_1 - ae^{kM})(\beta - \alpha) + \varphi_2\xi\alpha]}{\xi^2[m(1 - f)\varphi_2 - (\beta - \alpha)\phi_1^2]} 
\]  

(19)
We can infer from formula (12) and Appendix (Proof of Theorem 4) that \( f^*_3 \) has nothing to do with \( a \) and \( c \), and all other decision variables have declined with deferred payment compared with those with ample cash except the subsidy rate of emission reduction.

See appendix for detailed expressions.

5. Results and comparison. According to the results obtained in Section 4, we compare the above three different cases in details, and then some practical implications in operation and management can be achieved based on the actual situation of engineering machinery industry in China. We concentrate on the effects of carbon abatement investment and capital levels on profits and social welfare, and some significant conclusions are derived through comparison.

5.1. The value of carbon abatement investment.

**Proposition 1.** (1) The recycling quantities of Models I and II satisfy: \( R^*_2 > R^*_1 \). (2) The profits of the remanufacturer in Models I and II satisfy: \( \pi^*_2 > \pi^*_1 \). (3) The profits of the third-party recycler in Models I and II satisfy: \( \pi^*_3 > \pi^*_1 \).

In Proposition 1, the recycling quantity and profit of the remanufacturer and the third-party recycler with abatement investment are always higher than those without abatement investment. It indicates that investment in emission reduction may be an effective measure and meaningful marketing method to promote the remanufacturer’s recycling and production for more profits for the remanufacturer and the third-party recycler. (Proof see Appendix)

**Proposition 2.** (1) The total emissions of Models I and II satisfy: \( E^*_1 > E^*_2 \). (2) The social welfare of Models I and II satisfy: \( sw^*_1 < sw^*_2 \).

Proposition 2 (1) concludes that the total emission without abatement investment exceeds the carbon emission of Model II, which demonstrates that abatement investment can availably decrease the total emission of the remanufacturer. According to proposition 2 (2), we can also know that the social welfare of Model II is always larger than the value in Model I. On one hand, this is due to the emission reduced by abatement investment and corresponding environmental benefits increasing, on the other hand, abatement investment promotes the carbon emission trading. Thus, the social welfare of Model II may increase correspondingly. (Proof can be seen in Appendix)

5.2. The impact of payment delay. In this section, we make a comparison of production and emission reduction with and without delay paying in a remanufacturing system. Specially, we mainly focus on discussing the results of Model III (2) in which its initial cash is higher than that in Model III (1).

**Proposition 3.** (1) The recycling quantities of Models II and III satisfy: \( R^*_2 > R^*_1 \). (2) The levels of carbon reduction rate in Models II and III satisfy: \( \tau^*_2 > \tau^*_1 \). (3) The government subsidy rates for emission reduction in Models II and III satisfy: \( f^*_2 > f^*_1 \) and \( f^*_2 = f^*_3 \).
Proposition 3 (1) illustrates that according to the principle of the newsboy model, the final recycling quantity of the remanufacturer with capital constraint will be more than that without capital constraint. And the relationship between Model II and Model III (2) in reduction rate is similar to that in the recycling quantity. It demonstrates that capital constraint not only limits production but also dwindles emission reductions by the remanufacturer. As for the carbon subsidy rate by the government, proposition 3(3) shows that the value of case 2 of Model III with higher self-owned capital is equal to that of Model II, while the carbon emission subsidy with lower self-owned capital is less than that of Model II, which demonstrates that a higher self-owned capital promotes the subsidy of the government.

Proposition 4. (1) The levels of emission reduction in Models II and III satisfy:
\[ \Delta E^*_2 > \Delta E^*_3 \]. (2) The total emissions of Models II and III satisfy:
\[
\begin{cases}
E^*_2 > E^*_3 & \text{if } (M - \phi_3 N_1)N_1 > (M - \phi_3 N_2)N_2 \\
E^*_2 < E^*_3 & \text{if } (M - \phi_3 N_1)N_1 < (M - \phi_3 N_2)N_2
\end{cases}
\]
(21)
Where \( M = [m\phi_2 - \phi_1\phi_2(\beta - \alpha)]\xi, \ N_1 = (\phi_1 - a)(\beta - \alpha) + \alpha\xi\phi_2, \ N_2 = (\phi_1 - ae^{kM})(\beta - \alpha) + \alpha\xi\phi_2 \).

According to proposition 4 (1), we can know that capital constraint will weaken the carbon reduction level by the remanufacturer. Based on proposition 4 (2), we find that the total emission of the remanufacturer of Model II is less than the emission of Model III (2) if \((M - \phi_3 N_1)N_1 < (M - \phi_3 N_2)N_2\), which seems counter intuitive. Nevertheless, the remanufacturer’s total emission of Model II is higher than the value of Model III (2) as \((M - \phi_3 N_1)N_1 > (M - \phi_3 N_2)N_2\). It demonstrates that delay in payment may decrease the total emission of the remanufacturer when it satisfies a certain condition.

Considering the actual situation of engineering machinery industry in china, the comparison of total emission is given in the next two tables where parameter settings are the same as in Section 5. Actually, many engineering machinery enterprises in china have remanufacturing business department, such as Xugong Group and Weichai Power (see [34, 6]). They set up remanufacturing centers in more than one agent, remanufacturing and selling products in the recycling place, not only simplify the process but also reduce the transportation costs of heavy machinery. Thus, we can see that in Table 4 (as \( k = 0.2 \)), the cost of deferred payment financing is relatively low and the total emission in Model II is the least if \( m < 1400 \), which is shown as underlined data below. It illustrates that the delay in payment cannot effectively decrease the total emission when the carbon emission intensity is relatively low. Moreover, total carbon emission of Model III (1) presents the highest, which signifies that a lower self-owned capital may lead to a lower emission reductions and release more CO₂. However, when \( m > 1600 \), the total carbon emission of Model II is the largest while the value of Model III (1) is the smallest. That indicates that when the carbon reduction intensity is relatively larger than the previous value, a delay in payment can effectively alleviate financial issues and reduce carbon emissions in the case of capital constraints, especially in the case with lower self-owned capital. The corresponding graphs are given as below.

In addition, when \( k = 0.6 \), we notice that only when \( m \geq 1400 \), Model II’s total emission is the largest and the value of Model III(2) is the smallest, which differs from the presentation in Table 4. However, the total carbon emission of Model III(1) in Table 5 is equivalent to that in Table 4, while the value of Model
III(2) suffers a gently decline in Table 5. It indicates that a higher financing cost of deferred payment may effectively improve the emission efficiency and reduce the carbon emission by the remanufacturer, especially in the case with higher self-owned capital. Therefore, when the cost of deferred payment financing and the degree of emission efforts are both relatively high, a higher initial cash of Model III(2) is a preferred strategy from the perspective of total emission.

Table 4. The impact of m on the total emission (\(k = 0.2\))

| m  | 1200 | 1400 | 1600 | 1800 | 2000 |
|----|------|------|------|------|------|
| \(E^*_2\) | 19.9770 | 41.8060 | 53.7053 | 61.0017 | 65.8504 |
| \(E^{(1)}_3\) | 37.5510 | 40.3498 | 42.4490 | 44.0816 | 45.3878 |
| \(E^{(2)}_3\) | 29.5592 | 46.1639 | 55.1360 | 60.5937 | 64.1942 |

Notes: carbon emission unit: kilo

Table 5. The impact of m on the total emission (\(k = 0.6\))

| m  | 1200 | 1400 | 1600 | 1800 | 2000 |
|----|------|------|------|------|------|
| \(E^*_2\) | 19.9770 | 41.8060 | 53.7053 | 61.0017 | 65.8504 |
| \(E^{(1)}_3\) | 37.5510 | 40.3498 | 42.4490 | 44.0816 | 45.3878 |
| \(E^{(2)}_3\) | 34.0743 | 34.1072 | 33.8873 | 33.6214 | 33.3659 |

Notes: carbon emission unit: kilo

Proposition 5. (1) The profits of the remanufacturer in Models II and III satisfy: \(\pi^*_2 > \pi^{(2)}_3\). (2) The profits of the third-party recycler in Models II and III satisfy: \(\pi^*_2 < \pi^{(2)}_3\).

Based on proposition 5 (1), we can infer that the profit of the remanufacturer without capital constraint is always higher than that with capital constraint, which is similar to proposition 3 (1) and (2). This is understandable that capital constraint has a negative impact on the recycling and production of the remanufacturer. Different from the remanufacturer, the profit of the third-party recycler in Model III(2) with deferred payment is higher than that in Model II with varying m. Accordingly, deferred financing may be beneficial to the third-party recycler.

However, the third party recycler gives the remanufacturer a partial discount on the recycling price by deferred payment, while financing by the remanufacturer is for carbon abatement investment. Therefore, In view of economic and environmental factors, the remanufacturer’s profit is less than that with ample cash, while the recycler’s profit is higher. Furthermore, the profit with bigger initial cash is always bigger under the situation of deferred payment.

6. Numerical examples and sensitivity analysis. This section conducts a numerical analysis to specifically describe these three models. To investigate the impact of different parameters on production and reduction emission strategies, we preset the values of base parameters in Table 6. These parameters are stimulated by the cases in Zhou et al. [40] and Xiao et al. [32]. The remaining parameters are achieved by inquiring some enterprises in the engineering machinery enterprises in china, and some relative adjustments are made according to the actual situation of the industry.
Table 6. Present values for the base parameters \((e_t = 1)\)

| Parameter | \(p\) | \(c\) | \(a\) | \(c_0\) | \(h\) | \(s\) | \(v\) |
|-----------|-------|-------|-------|-------|-------|-------|-------|
| Present value | 40    | 8     | 2     | 1     | 2     | 1.6   | 1     |

Table 7. Comparison of the optimal solutions for varying values of \(k\) under two different self-owned capital strategies

| \(B\) | \(k\) | \(R\) | \(\tau\) | \(f\) | \(E\) | \(\Delta E\) | \(I\) | \(\pi_t\) | \(\pi_r\) | \(sw\) |
|-------|-------|-------|----------|-------|------|----------|-----|-------|-------|-------|
| (RMB) | (RMB) | (kilo) | (kilo) | (RMB) | (RMB) | (RMB) | (RMB) | (RMB) | (RMB) | (RMB) |
| \(B < \min(B_1, B_2)\), \(B_1 = 414.2992, B_2 = 583.7571\) | \(B > \max(B_2, B_3)\), \(B_2 = 586.0089, B_3 = 645.6875\) |
| 200 | 0.2 | 23.8095 | 0.1829 | 0.0833 | 31.1292 | 6.9660 | 22.9878 | 543.7939 | 62.9580 | 1365.8837 |
| 300 | 0.2 | 35.7143 | 0.2743 | 0.0833 | 41.4694 | 15.6735 | 51.7224 | 633.6119 | 94.4371 | 1365.8837 |
| 400 | 0.2 | 47.6190 | 0.3657 | 0.0833 | 48.3265 | 27.8639 | 91.9510 | 695.3773 | 1523.7365 |
| 400 | 0.6 | 47.6190 | 0.3657 | 0.0833 | 48.3265 | 27.8639 | 91.9510 | 292.7556 | 528.5379 | 1121.1148 |
| 700 | 0.2 | 69.7630 | 0.5408 | 0.0919 | 51.2557 | 60.3650 | 199.2045 | 737.4973 | 184.4698 | 1573.5686 |
| 800 | 0.2 | 69.7630 | 0.5408 | 0.0919 | 51.2557 | 60.3650 | 199.2045 | 737.4973 | 184.4698 | 1573.5686 |
| 900 | 0.2 | 69.7630 | 0.5408 | 0.0919 | 51.2557 | 60.3650 | 199.2045 | 737.4973 | 184.4698 | 1573.5686 |
| 900 | 0.6 | 26.6087 | 0.2011 | 0.0687 | 34.0100 | 8.5639 | 28.2608 | 342.0076 | 295.3374 | 1165.0597 |

6.1. Sensitivity to the self-owned capital and deferred payment length. In this subsection, we take the condition that \(m = 1500, M = 3\) and \(T = 3\) into account to explore the impact of self-owned capital and the sensitivity to deferred payment length on the optimal production and carbon reduction strategies in Table 7. We set \(k = 0.2\) and \(0.6, B\) belong to \([0, 400]\) when \(B < \min(B_1, B_2)\) and \(B\) belongs to \([700, 1000]\) when \(B > \max(B_2, B_3)\), while other parameters keep unchanged.

Table 7 suggests the following observations:

1. When \(B < \min(B_1, B_2)\), the recycling quantity, carbon reduction rate, total carbon emission, carbon abatement investment amount, profits and social welfare all gradually increase in the self-owned capital, while government subsidy rate keeps unchanged. It indicates that an increase in self-owned capital can actively promote the carbon reduction level and recycling by the remanufacturer. In addition, an increase in \(k\) may lead to a considerable loss of profits of the remanufacturer, while it leads to a significant growth in the profits of the third-party recycler, and other decision variables remain constant.

2. When the initial cash is relatively high, that is \(B > \max(B_2, B_3)\), all decision variables remain constant whatever changes of self-owned capital. While with an increase in \(k\), all other decision variables suffer a shrink to some extent, only the profits of the third-party recycler are significantly increased. It demonstrates that the increased financing cost may lead to a negative effect on remanufacturer’s willingness to recycle and reduce emissions. More specifically, carbon reductions and abatement investment amount suffer a sharp decrease, implying that compared with production decision, financing cost has a greater impact on abatement investment decision.
6.2. **Sensitivity to remanufacturing rate.** In order to discuss about the effects of remanufacturing rate and carbon trading price on the carbon emission difference and profit difference among three models, we pick $\xi = [0.2, 0.8]$, $c_m = 4$ or $c_m = 8$. Figure 4 to Figure 6 depict the curves of carbon emission differences and profit differences with varying remanufacturing rate when carbon trading price $c_m = 4$. Figure 7 to Figure 9 depict the curves of carbon emission differences and profits differences with a higher carbon trading price of $c_m = 8$.

As shown in Figure 4, the carbon emission difference between Model I and Model II ($E_1 - E_2$) is positive and gradually increases with the remanufacturing rate. The reason is that the increase in remanufacturing rate promotes the production, and the increasing behavior of the function up to a certain point shows that the implementation of carbon abatement investment can effectively curb the carbon emission level, but there exists a maximum potential to reduce emissions. In addition, the carbon emission difference between Model II and Model III ($E_2 - E_3$) is positive and presents a trend of decline in general, implying that deferred payment can effectively alleviate the carbon emission problem. Specifically, it can be seen that the value of carbon emission difference between Model II and Model III (1) is higher than that between Model II and Model III (2) when $\xi \geq 0.25$, implying that a higher initial cash may promote carbon emissions and the rate of emission growth is faster in Model III (2) than that in Model III (1).

Figure 5 illustrates that the profit difference of the remanufacturer between Model I and Model II ($\pi_{r1} - \pi_{r2}$) is negative and its absolute value gradually increases as the remanufacturing rate increases, illustrating that emission reduction can effectively...
dwindle emission cost and may be profitable for the remanufacturer, and the higher the remanufacturing rate is, the greater the profit advantage will be. Furthermore, the profit difference of the remanufacturer between Model II and Model III (1) \((\pi_{r2} - \pi^{(1)}_{r3})\) is positive and moderately increases, while the value between Model II and Model III (2) \((\pi_{r2} - \pi^{(2)}_{r3})\) slightly increases firstly and suffers a shrink later. This phenomenon demonstrates that deferred payment may not play a positive role in the remanufacturer’s profits.

Different from Figure 5, the profit difference of the third-party recycler between Model I and Model II \((\pi_{t1} - \pi_{t2})\) in Figure 6 is negative and its absolute value dwindles in the remanufacturing rate, showing emission reduction can effectively increase recycling quantity and may be beneficial to the third-party recycler. In addition, the profit differences curve of the recycler between Model II and Model III \((\pi_{t2} - \pi_{t3})\) imply that a delay in payment may bring the third-party recycler more profits. Specially, compared with the case of \(B < B_2\), the value between Model II and Model III (2) presents a trend of rapid decline firstly and increases later with the remanufacturing rate, which reveals that with a higher self-owned capital, the greater the varying \(\xi\) on the influence of the third-party recycler’s profit will be, and the recycler may have a greater profit advantage.

\[\]

**Figure 6.** Comparison of profit differences of the third-party recycler under different models for varying values of \(\xi\) when \(c_m = 4\).

Compared with the changes in Figure 4, Figure 7 show that with an increment in trading price, the carbon emission differences between Model II and Model III are positive firstly but negative later and present different tendencies in Model III(1) and Model III(2), implying that when the remanufacturing rate exceeds a certain value, delay in payment may not effectively reduce carbon emissions. In addition, the curve of emission difference in Model III(1) intersects the curve in Model III(2),
Figure 7. Comparison of emission differences under different models when $c_m = 8$.

Figure 8. Comparison of profit differences of the remanufacturer under different models when $c_m = 8$.

Figure 9. Comparison of profit differences of the third-party recycler under different models when $c_m = 8$. 
revealing that a bigger initial cash may not necessarily bring out higher emissions all the time, which seems run counter to the common sense.

However, compared with the curves of Figure 5, the change tendency of profit difference of the remanufacturer between Model I and Model II in Figure 8 illustrates that the higher trading price is, the greater influence of remanufacturing rate on the profit will be. Furthermore, the profit difference between Model II and Model III (2) rapidly increases firstly but moderately declines later, which reveals that an increase in trading price undermines the advantage of a higher self-owned capital.

In Figure 9, with a higher trading price, the profit gaps of the recycler between Model II and Model III are smaller as remanufacturing rate increases compared with the curves in Figure 6, implying that the profit advantage is less obvious with deferred payment.

7. **Discussion.** By comparing the remanufacturer’s carbon emissions and profits in the case of abatement investment and deferred payment to those when no investment and capital constraint are available, we derive several interesting managerial insights. The most desired outcome is that abatement investment is effective, reflected by not only the decrease by the regulatory policy but also the decrease in carbon emissions though the profit and social welfare increase, which indicates that there is a better incentive for the government to support investment decision. From the perspective of financing, deferred payment may always beneficial to the third-party recycler, which can effectively expand its market sales capacity. Because the financing interest rate charged by the third-party recycler usually increases during the credit period. However, it is worth noting that the remanufacturer’s profit is shrinking compared with the traditional newsvendor model owing to financing cost. It means that though deferred payment can alleviate financial issue and enhance channel efficiency, it may not be profitable to all parties in the system. In addition, the remanufacturer’s initial capital may play a significant role in decision results. With a higher self-owned capital, both the remanufacturer and the third-party recycler have a greater profit advantage, while it may not always lead to higher carbon emissions, which is counter intuitive to our common sense.

To the best our knowledge, though previous researches have made some contributions to the areas of carbon reduction and trade credit, our paper is an initial attempt to link trade credit with remanufacturing and abatement investment in a remanufacturing system consisting of a third party recycler and a capital-constrained remanufacturer. However, our paper face some limitations. In this paper, deferred payment is only regarded as a financing approach to support the expenditures required for his carbon reduction. Although the effects of the sensitivity of deferred payment length on the optimal carbon emissions and profits are studied in this paper, it is worth considering the setting under which the length of the credit period is determined endogenously. Besides, as an important part of trade credit coordination, the default risk of trade credit should be taken into account in the subsequent research. Moreover, while facing the shortage of working capital by the remanufacturer, there only considers one kind of financing channel by trade credit, which can be expanded to multiple alternative channels of financing and portfolio financing.

8. **Conclusion.** In this paper, we study a remanufacturing system in which a financially constraint remanufacturer who makes recycling, remanufacturing and carbon abatement investment operating with deferred payment to the third-party recycler.
Accordingly, a nonlinear optimization model based on profit is conducted and analytical expressions for the optimal recycling quantity, carbon reduction rate and government subsidy rate are presented respectively by using the backward induction. Based on above analysis, numerical experiments are employed to analyze how the remanufacturer’s carbon emissions and profits in the case of abatement investment and deferred payment are compared to those when no investment and capital constraint are available.

From a managerial point of review, the remanufacturer can always make use of the investment option to further decrease its carbon emissions and increase its recycling quantity and profit. But the concavity of carbon emission difference curve implies that the cost of cutting emissions is getting higher and higher. Thereafter, in the case of capital constraint, deferred payment can effectively alleviate the financial issue and reduce carbon emissions only when the degree of emission efforts is more than a certain critical value, and it also plays a positive role in the third-party recycler’s revenue, especially for the case with higher self-owned capital. In addition, the results also indicate that the higher the remanufacturing rate and trading price is, the more obvious the remanufacturer’s profits advantage of abatement investment will be. The results of this paper illustrate the close linage between operational and financial aspects in a remanufacturing system, which should be considered by employing integrated planning approach.

In the further, we can design the length of credit period as the decision variable and explore the impacts of different financing channel and default risk on the remanufacturer’s emissions and profitability of the remanufacturer system. Other results on the operational and financial implications presented in this paper may also serve as hypotheses for further empirical researches.

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Appendix. Proof of Theorem 1. To show that the objective function (1) is concave, we need to prove that its second derivative with respect to the recycling quantity is negative (see A. 2). The first and the second derivative of the objective function (1) are given below:

\[
\frac{\partial \pi_{r1}}{\partial R} = (p - c + c_0)\xi - a - c_0 + s\xi - c_0c_m\xi - (p + h + s)F(R\xi)\xi \quad (A.1)
\]

\[
\frac{\partial^2 \pi_{r1}}{\partial R^2} = -(p + h + s)f(R\xi)\xi^2 < 0 \quad (A.2)
\]

It is obvious that the second derivative is negative the objective function (1) is concave.

Proof of Lemma 1. To show that the objective function (5) is concave, we need to prove that its Hessian is positive demi-definite (see A. 6). The Hessian matrix of
the objective function (5) are given below:

\[ \det(\pi_{r2}) = \begin{vmatrix} \frac{\partial^2 \pi_{r2}}{\partial R^2} & \frac{\partial^2 \pi_{r2}}{\partial R \partial \tau} \\ \frac{\partial^2 \pi_{r2}}{\partial \tau^2} & \frac{\partial^2 \pi_{r2}}{\partial \tau} \end{vmatrix} = \begin{vmatrix} -(p + h + s) f(R \xi) \xi^2 c_{m + \delta}^2 & e_0 \xi c_{m + \delta} + \delta e_0 \xi \\ e_0 \xi c_{m + \delta} + \delta e_0 \xi & -(1 - f)m \end{vmatrix} \]

\[ = (p + h + s) f(R \xi) \xi^2 (1 - f)m - e_0^2 \xi^2 (c_{m + \delta})^2 \]  
(A.3)

\[ \frac{\partial^2 \pi_{r2}}{\partial R^2} = -(p + h + s) f(R \xi) \xi^2 < 0 \]  
(A.4)

\[ \frac{\partial^2 \pi_{r2}}{\partial \tau^2} = -(1 - f)m < 0 \]  
(A.5)

Matrix \( \det(\pi_{r2}) \) is positive demi-definite if and only if it satisfies the condition of C1:

\[ (p + h + s) f(R \xi) (1 - f)m \geq e_0^2 (c_{m + \delta})^2 \]  
(A.6)

**Proof of Theorem 2.** If \( x \sim U(\alpha, \beta) \), we can derive the first derivatives of the objective function (5) respect to the recycling quantity and carbon reduction rate:

\[ \frac{\partial \pi_{r2}}{\partial R} = (p + c + e_0) \xi - a - c_0 + s \xi - e_0 c_{m} (1 - \tau) \xi + \delta e_0 \xi \tau - (p + h + s) F(R \xi) \xi \]

(A.7)

\[ \frac{\partial \pi_{r2}}{\partial \tau} = (e_0 \xi c_{m + \delta} + \delta e_0 \xi) R - (1 - f)m \tau \]

(A.8)

Thus, we put the optimal solutions of recycling quantity and carbon reduction rate into the function of social welfare (6). In order to prove that its second derivative with respect to the government subsidy rate is negative (see A. 10). The first and the second derivative of the social welfare (6) are given below:

\[ \frac{\partial sw_2}{\partial f} = \begin{cases} (c_{m + \delta})^2 e_0^2 m \left[ \left( (p + c + e_0) (\alpha - \delta) + (1 - f)m (p + h + s) \right) \right] \\ + \left( (p + h + s) \xi (\alpha - \delta) \right) + \left( (a + c_0) \xi (\alpha - \delta) + (p + h + s) \xi \alpha \right) + \left( m (p + h + s) (2f (c_{m + \delta}) + 1) \right) \right] \]

\[ \frac{\partial^2 sw_2}{\partial f^2} = \begin{cases} (c_{m + \delta})^2 e_0^2 m \left[ \left( (p + c + e_0) (\alpha - \delta) + (1 - f)m (p + h + s) \right) \right] \right] \\ + \left( (p + h + s) \xi (\alpha - \delta) \right) + \left( (a + c_0) \xi (\alpha - \delta) + (p + h + s) \xi \alpha \right) + \left( m (p + h + s) (2f (c_{m + \delta}) + 1) \right) \right] \]

(A.9)

The second derivative of the social welfare is negative if and only if it satisfies the condition of C2:

\[ m (p + h + s) [c_{m} (2f + 1) + \delta (4f - 1)] > e_0^2 (c_{m + \delta}) (c_{m + \delta})^2 (\beta - \alpha) \]

(A.11)

Thus, the function of social welfare is concave and we derive the optimal solution of \( f_{r2}^* \) and the corresponding optimal solutions of \( R_{r2}^* \) and \( \tau_{r2}^* \) with the given \( f_{r2}^* \).

**Proof of Lemma 2.** In order to show the objective function (11) is differentiable and concave, we need to prove that its Hessian matrix is positive semidefinite. Furthermore, the initial cash constraint is also differentiable, and it is concave in \( R \) and \( \tau \) because its Hessian matrix

\[ \begin{bmatrix} 0 & 0 \\ 0 & (1 - f)m \end{bmatrix} \]

is negative semi-definite.
The multipliers \( \lambda \) satisfies the condition of the Karush-Kuhn-Tucker (KKT) optimality conditions below.

\[
\begin{align*}
\text{Det}(\pi_{r3}) &= \begin{vmatrix}
\frac{\partial^2 \pi_{r3}}{\partial R^2} & \frac{\partial^2 \pi_{r3}}{\partial R \partial \tau} \\
\frac{\partial^2 \pi_{r3}}{\partial \tau^2} & \frac{\partial^2 \pi_{r3}}{\partial \tau \partial R}
\end{vmatrix} = \begin{vmatrix}
-(p + h + s)f(R\xi)\xi^2 & e_0\xi c_m + \delta e_0\xi \\
e_0\xi c_m + \delta e_0\xi & -(1 - f)m
\end{vmatrix} \\
&= (p + h + s)f(R\xi)\xi^2(1 - f)m - e_0^2\xi^2(c_m + \delta)^2 \tag{A.12}
\end{align*}
\]

The same as before, matrix \( \text{Det}(\pi_{r3}) \) is positive demi-definite if and only if it satisfies the condition of C1:

\[
(p + h + s)f(R\xi)(1 - f)m \geq e_0^2(c_m + \delta)^2 \tag{A.15}
\]

Thus, the objective function (11) exists the optimal solutions by taking advantage of the Karush-Kuhn-Tucker (KKT) conditions below.

**Proof of Theorem 3.** If \( x \sim U(\alpha, \beta) \), respect to the prove mentioned above, we conduct the KKT optimality conditions below to ensure the global optimality together with the feasible conditions.

\[
\begin{align*}
(p - c + c_0)\xi - ae^{kM} - c_0 + s\xi - e_0c_m(1 - \tau)\xi \\
+ \delta e_0\xi\tau - (p + h + s)F(R\xi)\xi - \lambda_1(a + c\xi) - c\xi\lambda_2 &= 0 \tag{A.16}
\end{align*}
\]

\[
\begin{align*}
(e_0\xi c_m + \delta e_0\xi)R - (1 + \lambda_2)(1 - f)m\tau &= 0 \tag{A.17}
\end{align*}
\]

\[
\begin{align*}
\lambda_1[B - (a + c\xi)R] &= 0 \tag{A.18}
\end{align*}
\]

\[
\begin{align*}
\lambda_2[B - cR\xi - \frac{1}{2}(1 - f)m\tau^2] &= 0 \tag{A.19}
\end{align*}
\]

\[
\begin{align*}
B - (a + c\xi)R &\geq 0 \tag{A.20}
\end{align*}
\]

\[
\begin{align*}
B - cR\xi - \frac{1}{2}(1 - f)m\tau^2 &\geq 0 \tag{A.21}
\end{align*}
\]

\[
\begin{align*}
\lambda_1, \lambda_2 &\geq 0 \tag{A.22}
\end{align*}
\]

The multipliers \( \lambda_1, \lambda_2 \) may be equal or greater than zero. Considering all these alternatives, we derive four possible cases, however, there are only two cases that may result in feasible solutions.

**Case 1 when \( \lambda_1 > 0, \lambda_2 = 0 \),** the initial cash of the remanufacturer is equal to the cost of recycling and production and is sufficient for production and emission reduction. The optimal solutions of the recycling quantity and reduction rate \((R_{31}^{(1)}, \tau_{31}^{(1)})\) and \( \lambda_1 \) are obtained as:

\[
\begin{align*}
R_{31}^{(1)} &= \frac{B}{a + c\xi} \tag{A.23}
\end{align*}
\]

\[
\begin{align*}
\tau_{31}^{(1)} &= \frac{Be_0\xi(c_m + \delta)}{m(a + c\xi)(1 - f)} \tag{A.24}
\end{align*}
\]

\[
\begin{align*}
\lambda_1^{(1)} &= \frac{(p - c + c_0 + s - e_0c_m)\xi - ae^{kM} - c_0}{m(1 - f)(a + c\xi)} + \frac{Be_0^2\xi^2(c_m + \delta)^2}{m(1 - f)(a + c\xi)} - (p + h + s)\xi \frac{B\alpha - \alpha(a + c\xi)}{(\beta - \alpha)(a + c\xi)} \tag{A.25}
\end{align*}
\]
And the initial capital satisfies:

$$B < \frac{2am(1-f)}{\xi^2\phi_1^2}$$

where we define

$$B_1 = \frac{2am(1-f)}{\xi^2\phi_1^2}$$

(A.26)

$$R_{3}^{(1)} \geq 0, \; \tau_{3}^{(1)} \geq 0$$

are always satisfied, while \( \lambda_1 \geq 0 \), when:

$$B < B_2 = \frac{m(1-f)(a+c\xi)[(\varphi_1 - acMK)(\beta - \alpha) + \varphi_2\xi\alpha]}{\xi^2[m(1-f)\varphi_2 - (\beta - \alpha)\phi_1^2]}$$

(A.27)

Among, \( \varphi_1 = e_0(c_m + \delta) \), \( \varphi_2 = e_0(c_m + 3\delta) \), \( \varphi_3 = e_0(c_m + 3\delta) \) \( \varphi_1 = (p - c + e_0 + s - c_m e_0)\xi - e_0, \varphi_2 = p + h + s \). Based on the value range of all parameters, when Eq. (A. 26) and Eq. (A. 27) are satisfied, the recycling quantity and reduction rate in this case are the optimal results. Combing Eqs. (A. 23), (A. 24) and (13), the optimal total profit of the remanufacturer of Model III \( \pi_{r3}^{*} = \pi_{r3}^{(1)} \).

**Case 2 when \( \lambda_1 = 0, \lambda_2 = 0 \)**, the initial cash of the remanufacturer is equal to the cost of recycling and production and is also just right equal to that of production and emission reduction. The optimal solutions of the recycling quantity and reduction rate \( (R_{3}^{(2)}, \tau_{3}^{(2)}) \) are obtained as:

$$R_{3}^{(2)} = \frac{m(1-f)[(\varphi_1 - acMK)(\beta - \alpha) + \varphi_2\xi\alpha]}{\xi^2[m(1-f)\varphi_2 - (\beta - \alpha)\phi_1^2]}$$

(A.28)

$$\tau_{3}^{(2)} = \frac{\varphi_1[(\varphi_1 - acMK)(\beta - \alpha) + \varphi_2\xi\alpha]}{\xi[m(1-f)\varphi_2 - (\beta - \alpha)\phi_1^2]}$$

(A.29)

$$R_{3}^{(2)} \geq 0, \; \tau_{3}^{(2)} \geq 0$$

are always satisfied and the initial capital satisfies:

$$B > B_2 = \frac{m(1-f)(a+c\xi)[(\varphi_1 - acMK)(\beta - \alpha) + \varphi_2\xi\alpha]}{\xi^2[m(1-f)\varphi_2 - (\beta - \alpha)\phi_1^2]}$$

(A.30)

And

$$B > B_3 = \frac{m(1-f)[(\varphi_1 - acMK)(\beta - \alpha) + \varphi_2\xi\alpha]}{\xi[m(1-f)\varphi_2 - (\beta - \alpha)\phi_1^2]}$$

$$\left\{ c + \frac{e_0^2(c_m + \delta)^2[(\varphi_1 - acMK)(\beta - \alpha) + \varphi_2\xi\alpha]}{2\xi[m(1-f)\varphi_2 - (\beta - \alpha)\phi_1^2]} \right\}$$

(A.31)

Based on the value range of all parameters, when Eq. (A. 30) and Eq. (A. 31) are satisfied, the recycling quantity and reduction rate in this case are the optimal results. Combing Eqs. (A. 28), (A. 29) and (13), the optimal total profit of the remanufacturer of Model III \( \pi_{r3}^{*} = \pi_{r3}^{(2)} \).

**Proof of Theorem 4.** The same as Theorem 2, we put the optimal solutions of recycling quantity and carbon reduction rate into the function of social welfare (13). In order to prove that its second derivative with respect to the emission reduction subsidy rate is negative (see A. 33 and A. 37). The first and the second derivative of the social welfare (13) of case 1 are given as follows:

$$\frac{\partial sw_3^{(1)}}{\partial f} = \frac{e_0^2B^2\xi^2(c_m + \delta)[f(c_m + 2\delta) - \delta]}{m(1-f)^3(a + c\xi)}$$

(A.32)

$$\frac{\partial^2 sw_3^{(1)}}{\partial f^2} = \frac{e_0^2B^2\xi^2(c_m + \delta)[2f(c_m + 2\delta) + (c_m - \delta)]}{m(1-f)^4(a + c\xi)^2}$$

(A.33)

If the condition of C2 is satisfied, thus \( 2f(c_m + 2\delta) + (c_m - \delta) > 0 \). The second derivative of the social welfare \( sw_3^{(1)} \) is negative. Therefore, the function of social welfare...
welfare $sw_3^{(1)}$ is concave, and we derive the optimal solution of $f_3^{(1)}$ and the corresponding optimal profit of Model III(1). Specially, the optimal solutions of $R_3^{(1)}$ and $\tau_3^{(1)}$ are independent of $f_3^{(1)}$.

$$f_3^{(1)} = \frac{\delta}{c_m + 2\delta}$$
$$\tau_3^{(1)} = \frac{B\xi\phi_3}{m(a + c\xi)}$$

Similarly, the first and the second derivative of the social welfare (13) of case 2 are given below:

$$\frac{\partial sw_3^{(2)}}{\partial f} = -\frac{(c_m + \delta)e_0^2m\{(p - c + c_0 + s - e_0c_m)\xi - (ae^{km} + c_0)(\beta - \alpha) + (p + h + s)\xi\alpha\}^2[(c_m + \delta)^2\delta e_0^2(\alpha - \beta)]}{\delta^2[(c_m + \delta)^2e_0^2(\alpha - \beta) + (1 - f)m(p + h + s)]^3}$$

$$\frac{\partial^2 sw_3^{(2)}}{\partial f^2} = -\frac{(c_m + \delta)e_0^2m^2(p + h + s)\{(p - c + c_0 + s - e_0c_m)\xi - (ae^{km} + c_0)(\beta - \alpha) + (p + h + s)\xi\alpha\}^2(m(p + h + s) + 2f(c_m + 2\delta) + (c_m - \delta) + e_0^2(c_m + 5\delta)(c_m + \delta)^2(\alpha - \beta))}{\delta^2[(c_m + \delta)^2e_0^2(\alpha - \beta) + (1 - f)m(p + h + s)]^4}$$

The second derivative of the social welfare $sw_3^{(2)}$ is negative if and only if it satisfies the condition of C2.

As a result, we derive the optimal solution of $f_3^{(2)}$, and the corresponding optimal solutions of $R_3^{(2)}$, $\tau_3^{(2)}$, and the optimal profit of Model III(2) with the given $f_3^{(2)}$.

$$f_3^{(2)} = \frac{\delta(\phi_1^2(\beta - \alpha) + m\phi_2^2)}{m\phi_2^2(c_m + 2\delta)}$$

$$R_3^{(2)} = \frac{[m\phi_2^2 - e_0\delta\phi_1(\beta - \alpha)][(\phi_1 - ae^{km})(\beta - \alpha) + a\xi\phi_2]}{[m\phi_2^2 - \phi_1\phi_2(\beta - \alpha)]\phi_2^2\xi^2}$$

$$\tau_3^{(2)} = \frac{\phi_1[(\phi_1 - ae^{km})(\beta - \alpha) + a\xi\phi_2]}{[m\phi_2^2 - \phi_1\phi_2(\beta - \alpha)]\xi}$$

**Proof of Proposition 1.** In order to make a comparison between Model I and II, we should note that the optimal solutions of Model II must satisfy the conditions of C1 and C2, thus the comparison between Model I and II satisfies:

$$(1) \quad \frac{R_2}{R_1} = \frac{m(p + h + s) - e_0^2\delta(c_m + \delta)(\beta - \alpha)}{m(p + h + s) - e_0^2\delta(c_m + 3\delta)(c_m + \delta)(\beta - \alpha)} > 1$$

Where $\beta > \alpha$, thus $R_2^* > R_1^*$.

(2) It follows from the expression for $\pi_{r2}(R_2, \tau_2, f_2)$ and $\pi_{r1}(R_1, 0, 0)$ that $\pi_{r2}(R_2^*, \tau_2^*, f_2^*) > \pi_{r2}(R_1^*, 0, 0)$. Furthermore, it is obvious that $\pi_{r2}(R_1^*, 0, 0) = \pi_{r1}(R_1^*, 0, 0)$; thus, we have $\pi_{r2}(R_2^*, \tau_2^*, f_2^*) > \pi_{r1}(R_1^*, 0, 0)$.

(3) $\pi_{r2} - \pi_{r1} = (a - \nu_1)(R_2^* - R_1^*)$. Thus the comparison of $\pi_{r2}^*$ and $\pi_{r1}^*$ depends on the relative size of $R_2^*$ and $R_1^*$ according to $a - \nu_1 > 0$. Because $R_2^* > R_1^*$, thus we have $\pi_{r2}^* > \pi_{r1}^*$.

**Proof of Proposition 2.**
In order to compare the relationship between $E^*_2$ and $E^*_1$, we should compare the expressions of $(1 - \tau_2)R^*_2$ and $R^*_1$. Because
\[
0 < \frac{R^*_1}{R^*_2} = \frac{m(p + h + s) - e^0_\delta(c_m + 3\delta)(c_m + \delta)(\beta - \alpha)}{m(p + h + s) - e^0_\delta(c_m + 3\delta)(c_m + \delta)(\beta - \alpha)} < 1,
\]
0 < 1 - $\tau_2^*$
\[
= 1 - \left\{ \left[ (p - c + c_0 + s - c_m e_0) - \frac{1}{2}(a e^{kM} - c_0) \right] (\beta - \alpha) + \alpha(p + h + s) \right\} < 1,
\]
and $\left[ (p - c + c_0 + s - c_m e_0) - \frac{1}{2}(a e^{kM} - c_0) \right] (\beta - \alpha) + \alpha(p + h + s) > 0$, thus we have $R^*_1 < 1 - \tau_2^*$. Thus $E^*_2 < E^*_1$.

(2) $sw^*_2 - sw^*_1 = \tau_2 c_m E_{02}(q) + 2\tau_2 E_{02}(q)\delta - \frac{1}{2}m\tau_2^2 + (a - v_1)(R^*_2 - R^*_1)$. Thus the comparison of $sw^*_2$ and $sw^*_1$ depends on the relative size of the expression of $\tau_2 c_m E_{02}(q) + 2\tau_2 E_{02}(q)\delta - \frac{1}{2}m\tau_2^2 + (a - v_1)(R^*_2 - R^*_1)$. In order to ensure the effectiveness and feasibility of abatement investment by the remanufacturer, Model II should satisfy the condition of $c_m E_m(q) + \tau_2 E_{02}(q)\delta > \frac{1}{2}(1 - f_2)\delta$. Thus, we have $\tau_2 c_m E_{02}(q) + 2\tau_2 E_{02}(q)\delta > \frac{1}{2}m\tau_2^2$. Also, as shown in proposition 1, $(a - v_1)(R^*_2 - R^*_1) > 0$, thus we have $sw^*_2 > sw^*_1$.

**Proof of Proposition 3.** Before comparing Model II with III, we should note that $e^{kM} > 1$, thus the comparison of the decision variables between Model II and III satisfies:

(1) $R^*_3 < R^*_2$ and $\tau^*_3 < \tau^*_2$, thus, it is obvious that $\Delta E^*_3 < \Delta E^*_2$.

(2) $E^*_3 = (1 - \tau^*_3)\xi R^*_3$, we can see that the comparison of $E^*_3$ and $E^*_2$ depends on the expressions of $(1 - \tau^*_3)R^*_3$ and $(1 - \tau^*_2)R^*_2$. Thus we can obtain the following results:

Case 1: if $(M - \phi_3 N_1)N_1 > (M - \phi_3 N_2)N_2$, we have $(1 - \tau^*_3) < R^*_2/(1 - \tau^*_2)$, thus $E^*_2 > E^*_3$.

Case 2: if $(M - \phi_3 N_1)N_1 < (M - \phi_3 N_2)N_2$, we have $(1 - \tau^*_3) > R^*_2/(1 - \tau^*_2)$, thus $E^*_2 < E^*_3$.

Where $M = [m\phi_2 - \phi_1\phi_2(\beta - \alpha)]\xi$, $N_1 = (\phi_1 - a)(\beta - \alpha) + \alpha\xi\phi_2$, $N_2 = (\phi_1 - ae^{kM})(\beta - \alpha) + \alpha\xi\phi_2$. 

**Proof of Proposition 4.**

(1) $\Delta E^*_3 = \frac{\tau^*_3}{\tau^*_2} R^*_3$, because $R^*_3 < R^*_2$ and $\tau^*_3 < \tau^*_2$, thus, it is obvious that $\Delta E^*_3 < \Delta E^*_2$.

(2) $\frac{E^*_3}{E^*_2} = \frac{(1 - \tau^*_3)\xi}{(1 - \tau^*_2)\xi} R^*_3$, we can see that the comparison of $E^*_3$ and $E^*_2$ depends on the expressions of $(1 - \tau^*_3)R^*_3$ and $(1 - \tau^*_2)R^*_2$. Thus we can obtain the following results:

Case 1: if $(M - \phi_3 N_1)N_1 > (M - \phi_3 N_2)N_2$, we have $(1 - \tau^*_3) < R^*_3/(1 - \tau^*_2)$, thus $E^*_2 > E^*_3$.

Case 2: if $(M - \phi_3 N_1)N_1 < (M - \phi_3 N_2)N_2$, we have $(1 - \tau^*_3) > R^*_3/(1 - \tau^*_2)$, thus $E^*_2 < E^*_3$.
Proof of Proposition 5.

(1) It follows from the expression for $\pi_{t3}(R_3, \tau_3, f_3)$ and $\pi_{t2}(R_2, \tau_2, f_2)$, and the solutions of $R_3^{*}, \tau_3^{*}, f_3^{*}[i = (1), (2)]$, that $\pi_{t2}(R_2^{*}, \tau_2^{*}, f_2^{*}) > \pi_{t2}(R_2^{(2)}, \tau_2^{(2)}, f_2^{(2)})$. Furthermore, because $ae^{kM} > 0$, thus we have $\pi_{t2}(R_2^{(2)}, \tau_2^{(2)}, f_2^{(2)}) > \pi_{t3}(R_3^{(2)}, \tau_3^{(2)}, f_3^{(2)})$; thus, $\pi_{t2}(R_2^{*}, \tau_2^{*}, f_2^{*}) > \pi_{t3}(R_3^{(2)}, \tau_3^{(2)}, f_3^{(2)})$.

(2) It follows from the expression for $\pi_{t3}(R_3)$ and $\pi_{t2}(R_2)$, and the solutions of $R_3^{[i = (1), (2)]}$, that $\pi_{t3}(R_3^{(2)}) > \pi_{t3}(R_2^{*})$. Furthermore, because $a - v_1 > 0$ and $e^{kM} > 1$, thus we have $\pi_{t3}(R_3^{(2)}) > \pi_{t2}(R_2^{*})$; thus, $\pi_{t3}(R_3^{(2)}) > \pi_{t2}(R_2^{(2)})$.

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