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RESEARCH ARTICLE

Pricing Models for a Two-Period Manufacturing and Remanufacturing Process Under Carbon Cap and Trade Mechanism

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ABSTRACT Under carbon cap and trade mechanism, collecting ratio and carbon cap seriously affect the decision of a manufacturer in a closed-loop supply chain. This paper constructs pricing models for manufacturing and remanufacturing products in the presence of carbon cap and trade mechanism, aiming to reveal the impact of the collecting ratio for the carbon emission. A manufacturer and a carbon-trade supplier are involved in a Stackelberg pricing game. First, a decision model without carbon trade is formulated. Judging conditions are shown for determining whether carbon cap and collection ratio are effective factors. The two-sided impact of the collection ratio over the carbon emission is demonstrated. In practice, the manufacturer sometimes produces and sells a large proportion of new products by pricing strategies when facing a low collection ratio. Second, a Stackelberg game is played between the manufacturer and the carbon-trade supplier. We demonstrate that the decision model without carbon trade and the game model with carbon trade compose a complete decision process for the manufacturer. Finally, numerical illustrations are designed to examine the sensitivity of the carbon emission with respect to the collection ratio and determine the decision area when both the collection ratio and the carbon cap change.

INDEX TERMS Pricing strategy, carbon cap, carbon trade, collection ratio.

I. INTRODUCTION

Recent years, with growing concern over carbon emission, many countries and districts announce a series of policies on carbon tax and carbon trade. Carbon tax is a cost-effective governmental policy for the reduction of emissions and is highly recommended by many experts [1]. Under the carbon cap and trade mechanism, firms are first allocated a certain quantity of carbon emissions, and then they can purchase or sell on the carbon trading markets if they require more permits to produce more output or have surplus permits after production [2].

For environmental protection, cap-and-trade regulation is a feasible approach to reduce carbon emissions. We consider pricing decisions for a two-period manufacturing and remanufacturing process under this regulation in this study.

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Clearly, the price of carbon significantly affects the decision of the manufacturer. For example, in Guangdong Province of China, the guide price of carbon trade is set as 10∼50 yuan per ton for the sake of controlling the carbon emission of the manufacturing industry.

In response to these regulations, incorporating emission abatement into the production planning becomes indispensable concerning manufacturers' operational planning [3]. With the promotion of low carbon production, the effects of carbon emission on manufacturing and remanufacturing decisions attract many attentions [4]. Remanufacturing is a process by which used products are recovered, processed and sold as like-new products in the same or separate markets [5]. As a gradually maturing production form, remanufacturing plays an increasingly pivotal role in economy, environment and society [6]. In the remanufacturing process, collection ratio is an important factor, which affects the production quantity of the remanufactured product.

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In this study, we concern the production and pricing of manufacturing and remanufacturing products under cap-and-trade mechanism. A two-period manufacturing and remanufacturing process is considered. In period 1, the manufacturer only makes new products; while in period 2, both new products and remanufactured products are produced. The collection of the product which is sold in period 1 determines the production of the remanufactured product in period 2. A certain quantity of carbon emission is allocated to the manufacturer for his two-period manufacturing and remanufacturing process. When the carbon emission exceeds this quantity, carbon trade will occur, and a Stackelberg game is conducted between the manufacturer and a carbon-trade supplier.

There are some theoretical and practical contributions in this study. The first one is that we show the two-sidedness of the collection ratio over the carbon emission. The change of the collection ratio doesn't necessarily mean that the carbon emission will increase or decrease. Pricing strategies will be used to adjust the sales volume when the collection ratio turns into an effective factor. Dynamic pricing of the carbon trade is investigated with the amount of carbon trade changes. In addition, we show judging conditions for whether carbon trade is needed or not.

The reminder of this paper is organized as follows. In Section II, we provide a literature review to show the necessity of this research. Section III introduces the notations and makes some assumptions for the given setting. Pricing models without carbon trade are constructed in Section IV. In Section V, we propose game models on the premise that carbon trade occurs. Section VI designs numerical illustrations to examine the sensitivity of the carbon emission and the decision change. Section VII summarizes the study and shows the further research topics.

II. LITERATURE REVIEW

We consider a hybrid manufacturing-remanufacturing system involving a monopolist manufacturer and a carbon-trade supplier. Remanufacturing is a recovery process that transforms a used product into a "like-new" product [7]. In practice, many factors are involved when considering the product remanufacturing, such as carbon tax, production strategy, recycling mode, etc. It has been revealed that remanufacturing can effectively improve the level of carbon emission reduction [8]. This study mainly concerns carbon cap, carbon trade and collection ratio. The carbon cap-and-trade policy affects remanufacturing activities significantly, and it is an important driving factor in the remanufacturing process [9].

Two typical policies of governments for carbon control are cap-and-trade policy and carbon tax policy [10]. Reference [11] compared the two policies under different circumstances. We focus on the cap-and-trade policy in this paper. Under a cap-and-trade policy, a firm initially receives a number of permits for free, over a planning horizon, and is allowed to trade the permits with other firms or government agencies [12]. Although a cap-and-trade policy is designed to control carbon emission, it can also promote the remanufacturing indirectly [13]. Reference [14] examined the influence of cap-and-trade policy on collection activity outsourcing policy.

A two-period manufacturing and remanufacturing process is often adopted to handle the production and sales of a hybrid manufacturing-remanufacturing system. Reference [15] did a pioneering work for this topic, in which a firm made new products in the first period and used returned cores to offer remanufactured products along with new products in future periods. Reference [16] did an important job by formulating a two-period model to study the manufacturer's production strategy and the remanufacturer's pricing strategy. Reference [17] proposed a two-period production model under a carbon tax policy, and showed the effects of this policy on the optimal production decision. Reference [18] modeled a two-period manufacturing and remanufacturing problem on the premise that the tax price differs over the two periods. Reference [19] constructed stylized models for pure manufacturing and hybrid manufacturing-remanufacturing systems and brought some managerial insights by analyzing the results under different situations.

Pricing strategies are effective tools for adjusting the sales of new products and remanufactured products, which we also apply in this study. Reference [20] did a pioneering work for the price discrimination of remanufactured products. Reference [21] examined the pricing strategies of new and remanufactured products by considering consumers' preferences. Reference [22] considered the different willingness to pay for remanufactured products, and proposed a pricing decision model under the system of cap and trade. Reference [23] explored the optimal pricing and production decisions in a two-period horizon with the constraint of consumer participation. Similar to the above literature, pricing strategies are our main means to adjust production volume and carbon emissions.

Despite the abundant research with regard to the manufacturing-remanufacturing system under carbon cap-and-trade policy, there are still some research gaps:

(1) The impact of the collection ratio over the carbon emission remains to be examined. The correlation between production quantities of new products and remanufactured products will be tighter when the collection ratio turns into an effective factor. We use pricing strategies to adjust the demand when the collection ratio turns into an effective factor.

(2) Research for dynamic pricing of the carbon trade is not sufficient. Our study proposes a Stackelberg model to price the carbon emission. It is shown that the larger carbon trade the manufacturer needs, the higher sales price is claimed. Compared to the static pricing strategy, dynamic strategy generated by Stackelberg game is proved to be more effective to control the carbon emission.

TABLE 1. Model parameters.

Parameters/ variables	Definition
Parameters	
a	The potential market demand of each sales period
δ	The linear price-sensitive coefficient of the sales quantity
θ	The price substitution coefficient, showing the price competition level between different types of products, $0 < \theta < \delta$
μ	The preference proportion for the new product at the second stage. So, $1-\mu$ is the preference proportion for the remanufactured product.
c	The production cost per new product
s	The cost saving per remanufactured product. So, $c-s$ is unit production cost of the remanufactured product
e_1	The carbon emission for producing a new product
e_2	The carbon emission for producing a remanufactured product, $e_2 < e_1$
φ	The collection ratio ($0 < \varphi \leq 1$)
L	The carbon cap allocated to the manufacturer from the government
Variables	
p_1, q_1	The sales price and the production quantity of the new product in period 1, respectively
p_{2n}, q_{2n}	The sales price and the production quantity of the new product in period 2, respectively
p_{2r}, q_{2r}	The sales price and the production quantity of the remanufactured product in period 2, respectively
w	The sales price of one unit of carbon emission, declared by the carbon-trade supplier
q_e	The purchase quantity of the carbon emission

(3) The necessity of carbon trade under different circumstances lacks sufficient discussion. Our study shows that carbon cap and collection ratio are two crucial factors for the carbon trade.

III. MODEL DESCRIPTION AND ASSUMPTION

This paper discusses pricing and production of a two-period manufacturing and remanufacturing products involving a manufacturer and a carbon-trade supplier. A carbon cap allocated to the manufacturer is known information. The manufacturer makes decisions for whether carbon trade is needed, and the two participants play a Stackelberg game when carbon trade occurs.

The models of this paper are mainly based on the following assumptions.

Assumption 1: The demands of the following three are all positive: a. new products at period 1; b. new products at period 2; and c. remanufactured products at period 2.

Assumption 2: Both of the two participants possess complete information.

Assumption 3: The carbon-trade supplier in this paper refers to another firm or a government agency who possesses a sufficient carbon cap.

The notations used in the following discussion are given by the following table:

According to the above setting, we show the following formulations for each sales quantity: $q_1 = a - -\delta p_1$, $q_{2n} = \mu a – \delta p_{2n} + \theta p_{2r}$, and $q_{2r} = (1 - -\mu)a - -\delta p_{2r} + \theta p_{2n}$. The functions of q_{2n} and q_{2r} reflect the competition between new products and remanufactured products.

Clearly, φq_1 is the maximum number available for remanufacturing in period 2. Hence, $\varphi q_1 \geq q_{2r}$. It may be an effective condition, and we set $\varphi q_1 = q_{2r}$ in these situations. In the following discussion, we will show that the collection ratio plays an important role in the pricing decisions of the manufacturer. Similar to [3], the cost of the collection is not considered.

IV. PRICING MODELS WITHOUT CARBON TRADE

This section constructs integrated models for two-stage pricing cases without carbon trade. In this situation, the total carbon emission must be lower than or equal to L. The carbon-trade supplier is not involved in this scenario.

The pricing model of the manufacturer is presented as follows:

$$\max \pi_m = (p_1 - c)q_1 + (p_{2n} - c)q_{2n} + (p_{2r} - c + s)q_{2r}$$
$$s.t. \begin{cases} \varphi q_1 \geqslant q_{2r} \\ (q_1 + q_{2n})e_1 + q_{2r}e_2 \leqslant L \end{cases} \tag{1}$$

Clearly, model (1) can be solved by Karush–Kuhn–Tucker conditions. However, the value of each multiplier needs to be discussed separately. In order to analyze the critical state of the two constraints, we adopt another approach to deal with model (1).

First, we examine the objective function of model (1) without considering the constraints. The equation set of the partial derivative with regard to π_m is shown as follows:

The demand quantity of the new product under (1) is

$$\begin{cases} \dfrac{\partial \pi_m}{\partial p_1} = -2\delta p_1 + a + \delta c = 0 \\ \dfrac{\partial \pi_m}{\partial p_{2n}} = -2\delta p_{2n} + 2\theta p_{2r} + \mu a + \delta c - \theta(c-s) = 0 \\ \dfrac{\partial \pi_m}{\partial p_{2r}} = -2\delta p_{2r} + 2\theta p_{2n} + (1-\mu)a \\ \quad +\delta(c-s) - \theta c = 0 \end{cases}$$

By solving the above equation set, we obtain

$$\begin{cases} p_1 = \dfrac{a + \delta c}{2\delta} \\ p_{2n} = \dfrac{\mu\delta a + (1-\mu)\theta a + (\delta^2 - \theta^2)c}{2(\delta^2 - \theta^2)} \\ p_{2r} = \dfrac{(1-\mu)\delta a + \mu\theta a + (\delta^2 - \theta^2)(c-s)}{2(\delta^2 - \theta^2)} \end{cases} \tag{2}$$

The Hessian matrix of π_m is

$$H_1 = \begin{bmatrix} -2\delta & 0 & 0 \\ 0 & -2\delta & 2\theta \\ 0 & 2\theta & -2\delta \end{bmatrix}.$$

Because $-2\delta < 0$,

$$\begin{vmatrix} -2\delta & 0 \\ 0 & -2\delta \end{vmatrix} = 4\delta^2 > 0,$$

TABLE 2. Four possible cases of the two constraints.

	$\varphi q_1 \geq q_{2r}$ holds	$\varphi q_1 \geq q_{2r}$ holds
$(q_1+q_{2n})e_1+q_{2r}e_2 \leq L$ holds	Case 1: (Y, Y)	Case 2: (Y, N)
$(q_1+q_{2n})e_1+q_{2r}e_2 \leq L$ holds	Case 3: (N, Y)	Case 4: (N, N)

and

$$\begin{vmatrix} -2\delta & 0 & 0 \\ 0 & -2\delta & 2\theta \\ 0 & 2\theta & -2\delta \end{vmatrix} = -2\delta \begin{vmatrix} -2\delta & 2\theta \\ 2\theta & -2\delta \end{vmatrix} = -2\delta(4\delta^2-4\theta^2) < 0,$$

we know that H_1 is negative definite. Hence, the solution given by (2) is the unique solution of max π_m.

Next, we examine (2) by taking the constraints of model (1) into consideration. There are four possible cases, which are summarized by the following table:

In table 2, Y represents yes, and N represents no. In this section, we only consider Case 1 and part of Case 2 (we call it Case 2.1). Case 2.2, Case 3, and Case 4 will be discussed in the next section.

In order to guarantee that carbon trade is not needed, we show the following inequality condition:

$$\frac{[(1+\mu)a-2\delta c+\theta(c-s)]e_1}{2} + \frac{[(1-\mu)a-\delta(c-s)+\theta c]e_2}{2} \leqslant L. \tag{3}$$

If condition (3) doesn't hold, then skip the following content of this section and go straightly to the next section. The remainder of this section is based on condition (3).

In the following discussion of this section, we divide into two situations with regard to the first constraint of model (1) under condition (3).

***a*. The case$\varphi q_1 \geq q_{2r}$**

In this case, we have

$$\frac{(a-\delta c)\varphi}{2} \geqslant \frac{(1-\mu)a-\delta(c-s)+\theta c}{2}.$$

Namely,

$$\varphi \geqslant \frac{(1-\mu)a-\delta(c-s)+\theta c}{a-\delta c}. \tag{4}$$

According to the above discussion, (2) is the solution of model (1) when parameters meet both (3) and (4).

According to the above result, we draw the following conclusion:

Proposition 1: When both (3) and (4) hold, the constraints of the collection rate and the carbon cap are ineffective. Meanwhile, price decisions between period 1 and period 2 are uncorrelated.

We provide some causal analysis for the above conclusion. When the collection ratio is high enough, the production quantity of the remanufactured product in period 2 is not restricted to this factor. Actually, price decisions between period 1 and period 2 are interactive when either of the two constraints works.

***b*. The case$\varphi q_1 < q_{2r}$**

If (4) doesn't hold, (2) is not the solution of model (1). Apparently, the first constraint of model (1) is an effective constraint.

In this case, we show the following model:

$$\max \pi_m = (p_1-c)q_1+(p_{2n}-c)q_{2n}+(p_{2r}-c+s)q_{2r}$$
$$s.t. \begin{cases} \varphi q_1 = q_{2r} \\ (q_1+q_{2n})e_1+q_{2r}e_2 \leqslant L \end{cases} \tag{5}$$

By the equation constraint, we have

$$q_1 = \frac{(1-\mu)a-\delta p_{2r}+\theta p_{2n}}{\varphi}$$

and

$$p_1 = \frac{a}{\delta} - \frac{(1-\mu)a-\delta p_{2r}+\theta p_{2n}}{\varphi\delta}.$$

The objective function of model (5) is transformed to, as shown in the equation at the bottom of the next page.

We first handle this function without considering the inequality constraint of model (5). The equation set of the partial derivative with regard to πm is shown as follows:

$$\begin{cases} \frac{\partial \pi_m}{\partial p_{2n}} = -2(\frac{\theta^2}{\varphi^2\delta}+\delta)p_{2n}+2(\frac{\theta}{\varphi^2}+\theta)p_{2r} \\ +\frac{[\varphi-2(1-\mu)]\theta a-\varphi\delta\theta c}{\varphi^2\delta}+\mu a-\theta(c-s)+\delta c=0 \\ \frac{\partial \pi_m}{\partial p_{2r}} = -2(\frac{\delta^2}{\varphi^2\delta}+\delta)p_{2r}+2(\frac{\theta}{\varphi^2}+\theta)p_{2n} \\ +\frac{[2(1-\mu)-\varphi]\delta a+\varphi\delta^2 c}{\varphi^2\delta} \\ \quad +(1-\mu)a-\theta c+\delta(c-s)=0 \end{cases}$$

By solving it, we have

$$\begin{cases} p_{2n} = \frac{\mu\delta^3 a+(1-\mu)\delta^2\theta a+\delta^4 c-\delta^2\theta^2 c}{2(\delta^4-\delta^2\theta^2)} \\ p_{2r} = \frac{(\varphi^2+\varphi^4)\mu\delta^2\theta a+(1-\mu)(\varphi^2\theta^2+\varphi^4\delta^2)\delta a}{2(\varphi^2+\varphi^4)(\delta^4-\delta^2\theta^2)} \\ +\frac{2(1-\mu)\varphi^2\delta a-\varphi^3\delta a}{2(\varphi^2+\varphi^4)\delta^2} \\ +\frac{\varphi^3\delta^2 c+\varphi^2\delta\theta c+\varphi^4\delta^2(c-s)}{2(\varphi^2+\varphi^4)\delta^2} \end{cases} \tag{6}$$

The Hessian matrix of π_m is

$$H_2 = \begin{bmatrix} -2(\frac{\theta^2}{\varphi^2\delta}+\delta) & 2(\frac{\theta}{\varphi^2}+\theta) \\ 2(\frac{\theta}{\varphi^2}+\theta) & -2(\frac{\delta^2}{\varphi^2\delta}+\delta) \end{bmatrix}.$$

Because

$$-2(\frac{\theta^2}{\varphi^2\delta}+\delta) < 0$$

and

$$\begin{vmatrix} -2(\frac{\theta^2}{\varphi^2\delta}+\delta) & 2(\frac{\theta}{\varphi^2}+\theta) \\ 2(\frac{\theta}{\varphi^2}+\theta) & -2(\frac{\delta^2}{\varphi^2\delta}+\delta) \end{vmatrix} = 4(1+\frac{1}{\varphi^2})(\delta^2-\theta^2) > 0,$$

the solution given by (6) is the unique solution of max π_m.

Clearly, the point determined by (6) is the unique extreme point of π_m. If (6) meets the inequality constraint of model (5), it is the solution we hunt for. Otherwise, the inequality constraint is an effective constraint, i.e., the solution of model (5) may realize out of the boundary of the feasible region, and carbon trade is necessary, which we call Case 2.2. Decision models will be constructed for this situation in the next section.

In order to demonstrate the impact of "$\varphi q_1 = q_{2r}$" to the inequality constraint of carbon emission, we present each sales quantity as follows:

$$q_1 = \frac{(1-\mu)\varphi\delta^2 a + \delta^2 a - \delta^3 c + \varphi\delta^2\theta c - \varphi\delta^3(c-s)}{2(1+\varphi^2)\delta^2},$$

$$q_{2n} = \frac{\mu(1+\varphi^2)\delta^2 a + (1-\mu)\delta\theta a - \varphi\delta\theta a}{2(1+\varphi^2)\delta^2} + \frac{\varphi\delta^2\theta c + \delta\theta^2 c - (1+\varphi^2)\delta^3 c + \varphi^2\delta^2\theta(c-s)}{2(1+\varphi^2)\delta^2},$$

and

$$q_{2r} = \frac{(1-\mu)\varphi^2\delta^2 a + \varphi\delta^2 a - \varphi\delta^3 c + \varphi^2\delta^2\theta c - \varphi^2\delta^3(c-s)}{2(1+\varphi^2)\delta^2}.$$

Because of the complexity of q_1, q_{2n}, and q_{2r}, it is hard to compare the carbon emissions of **situation *a*** and **situation *b*** directly. We show the following counterintuitive conclusion and verify it in the numerical illustration section.

Suppose 1 The decrease of collection ratio may enhance the total carbon emission.

We provide some causal analysis for Suppose 1. When the collection ratio is low, the production quantity of the new product in period 1 is high and the production quantity of the remanufactured product in period 2 is low. With the increase of the collection ratio, the production quantity of the new product in period 1 will decrease within limits and the remanufactured product in period 2 will increase accordingly. These complex changes lead to the two-sided impact of the collection ratio over the carbon emission.

Suppose 1 is important, because according to this conclusion, the decision for whether carbon trade is needed may depends on the value of the collection ratio. When the collection ratio is low, the manufacturer may tend to produce more new products.

All the results obtained in this section are for cases in which carbon trade is not needed.

V. GAME MODELS IN THE PRESENCE OF CARBON TRADE

The Stackelberg game is considered between the manufacturer and the carbon-trade supplier, when condition (3) doesn't hold. In this situation, the carbon-trade supplier declares the price of one unit of carbon emission, and the manufacturer determines p_1, p_{2n}, p_{2r}, and q_e. The rest two cases in table 2 will be discussed.

We first consider Case 3 and Case 4 described by Table 2. Case 2.2 will be discussed in the latter part of this section, along with the special situations of Case 3 and Case 4. In reality, Case 2.2 could only happen in the situation when carbon trade is needed and meanwhile the collection ratio is an effective constraint, and we will show the reason later.

According to the given parameters, the manufacturer's procurement volume of the carbon emission is

$$q_e = (q_1 + q_{2n})e_1 + q_{2r}e_2 - L.$$

As the leader, the decision model of the carbon-trade supplier is

$$\begin{aligned} &\pi_s = w[(q_1+q_{2n})e_1 + q_{2r}e_2 - L] \\ &s.t.\ w \geqslant 0 \end{aligned} \tag{7}$$

As the follower, the decision model of the manufacturer is

$$\begin{aligned} \max \pi_m &= (p_1-c)q_1 + (p_{2n}-c)q_{2n} \\ &\quad + (p_{2r}-c+s)q_{2r} - wq_e \\ s.t. &\begin{cases} \varphi q_1 \geqslant q_{2r} \\ q_e \geqslant 0 \end{cases} \end{aligned} \tag{8}$$

(7) and (8) constitute a Stackelberg game. Clearly, $q_e \geq 0$ is a necessary constraint for the manufacturer. In special cases, the optimal decision of q_e may be zero when the carbon-trade supplier declares a relatively high w, and then the problem degenerates to the situation discussed in Section IV. Hence, model (1) and model (8) are complementary for the manufacturer, composing an impartible decision process. We will prove it theoretically in the end of this section.

In addition, under $q_e \geq 0$, $w \geq 0$ is a noneffective constraint for model (7). It's impossible for the carbon-trade supplier to declare a negative w, for the sake of maximizing π_s. Actually, $w > 0$ is a more practical constraint for model (7).

We first analyze the objective function of model (8) without considering its constraint. The equation set of the partial

$$\pi_m = \frac{[\varphi a - (1-\mu)a + \delta p_{2r} - \theta p_{2n} - \varphi\delta c][(1-\mu)a - \delta p_{2r} + \theta p_{2n}]}{\varphi^2\delta} + (p_{2n}-c)(\mu a - \delta p_{2n} + \theta p_{2r}) + (p_{2r}-c+s)[(1-\mu)a - \delta p_{2r} + \theta p_{2n}].$$

derivative with regard to π_m is shown as follows:

$$\begin{cases} \dfrac{\partial \pi_m}{\partial p_1} = -2\delta p_1 + a + \delta c + \delta e_1 w = 0 \\ \dfrac{\partial \pi_m}{\partial p_{2n}} = -2\delta p_{2n} + 2\theta p_{2r} + \mu a + \delta c - \theta(c-s) \\ +\delta e_1 w - \theta e_2 w = 0 \\ \dfrac{\partial \pi_m}{\partial p_{2r}} = 2\delta p_{2r} + 2\theta p_{2n} + (1-\mu)a + \delta(c-s) \\ -\theta c - \theta e_1 w + \delta e_2 w = 0 \end{cases}$$

The solution of the above equation set is obtained as follows:

$$\begin{cases} p_1 = \dfrac{a + \delta c + \delta e_1 w}{2\delta} \\ p_{2n} = \dfrac{\mu\delta a + (1-\mu)\theta a + (\delta^2-\theta^2)c + (\delta^2-\theta^2)e_1 w}{2(\delta^2-\theta^2)} \\ p_{2r} = \dfrac{(1-\mu)\delta a + \mu\theta a + (\delta^2-\theta^2)(c-s) + (\delta^2-\theta^2)e_2 w}{2(\delta^2-\theta^2)} \end{cases} \tag{9}$$

It is shown by (9) that p_1 and p_{2n} only relate to e_1, and p_{2r} only relates to e_2. When the constraint with respect to the collection rate works, the result will change.

The Hessian matrix of π_m is still H_1, which is negative definite. Thus, (9) is the unique extreme point of π_m.

By (9), we acquire the expression of q_e as follows:

$$q_e = \frac{[(1+\mu)a - 2\delta c + \theta(c-s) - 2\delta e_1 w + \theta e_2 w]e_1}{2} + \frac{[(1-\mu)a - \delta(c-s) + \theta c - \delta e_2 w + \theta e_1 w]e_2}{2} - L. \tag{10}$$

Because the premise of Case 2.2 is condition (3), and

$$\frac{(-2\delta {e_1}^2 + 2\theta e_1 e_2 - \delta {e_2}^2 + \theta e_1)w}{2} < 0$$

under $w > 0$. Hence, it's impossible for Case 2.2 to happen in this situation, otherwise $q_e < 0$, which doesn't meet the constraints of model (8).

By substituting (10) into the objective function of model (7), we have, as shown in the equation at the bottom of the next page.

Apparently, the solution of max π_s is

$$w = \frac{(1+\mu)ae_1 + (1-\mu)ae_2 + \theta(c-s)e_1 + \theta c e_2}{2(2\delta {e_1}^2 - 2\theta e_1 e_2 + \delta {e_2}^2)} - \frac{2\delta c e_1 + \delta(c-s)e_2 + 2L}{2(2\delta {e_1}^2 - 2\theta e_1 e_2 + \delta {e_2}^2)}. \tag{11}$$

By (9) and (11), the value of each sales quantity is obtained. Apparently, the Stackelberggame has a unique equilibrium.

By examining (10), the critical condition of q_e= 0is obtained as follows:

$$(1+\mu)ae_1 - 2\delta c e_1 + \theta(c-s)e_1 + (1-\mu)ae_2 - \delta(c-s)e_2 + \theta c e_2 = (2\delta {e_1}^2 - 2\theta e_1 e_2 + \delta {e_2}^2)w + 2L.$$

Hence, we get the upper bound of w:

$$w^* = \frac{(1+\mu)ae_1 + (1-\mu)ae_2 + \theta(c-s)e_1 + \theta c e_2}{2\delta {e_1}^2 - 2\theta e_1 e_2 + \delta {e_2}^2} - \frac{2\delta c e_1 + \delta(c-s)e_2 + 2L}{2\delta {e_1}^2 - 2\theta e_1 e_2 + \delta {e_2}^2}.$$

Proposition 2: $w > 0$ and $q_e > 0$ hold under (9).

Proof. The premise of this section till now is that condition (3) doesn't hold, i.e.,

$$\frac{[(1+\mu)a - 2\delta c + \theta(c-s)]e_1}{2} + \frac{[(1-\mu)a - \delta(c-s) + \theta c]e_2}{2} > L.$$

Moreover, according to $\delta > \theta > 0$ and $e_1 > e_2 > 0$, we have

$$2\delta {e_1}^2 - 2\theta e_1 e_2 + \delta {e_2}^2 > \delta {e_2}^2 > 0.$$

Thus, $w^* > 0$. Namely, w given by (11) is positive since $w = w^*/2$. In addition, as w given by (11) is lower than the critical value w^*, we have $q_e > 0$. □

Proposition 2 tells that $w \geq 0$ and $q_e \geq 0$ are ineffective constraints for model (7) and model (8).

If $\varphi q_1 \geq q_{2r}$ holds, (9) and (11) compose the equilibrium solution of the game. If $\varphi q_1 < q_{2r}$ under (9) and (11), $\varphi q_1 \geq q_{2r}$ is an effective constraint for model (8). Next, we deal with this situation when $\varphi q_1 \geq q_{2r}$ is an effective constraint. Actually, Case 2.2is also handled by the following approach.

The objective function of the carbon-trade supplier remains unchanged. The decision model of the manufacturer is

$$\max \pi_m = (p_1 - c)q_1 + (p_{2n} - c)q_{2n} + (p_{2r} - c + s)q_{2r} - wq_e \tag{12}$$
$$s.t. \begin{cases} \varphi q_1 = q_{2r} \\ q_e \geqslant 0 \end{cases}$$

By the equality constraint, the objective function of model (12) is transformed to, as shown in the equation at the bottom of the next page.

The equation set of the partial derivative with regard to π_m is shown as follows:

$$\begin{cases} \dfrac{\partial \pi_m}{\partial p_{2n}} = -2(\dfrac{\theta^2}{\varphi^2\delta} + \delta)p_{2n} + 2(\dfrac{\theta}{\varphi^2} + \theta)p_{2r} \\ +\dfrac{[\varphi - 2(1-\mu)]\theta a - \varphi\delta\theta c}{\varphi^2\delta} \\ +\mu a - \theta(c-s) + \delta c + (\delta - \dfrac{\theta}{\varphi})e_1 w \\ -\theta e_2 w = 0 \\ \dfrac{\partial \pi_m}{\partial p_{2r}} = -2(\dfrac{\delta^2}{\varphi^2\delta} + \delta)p_{2r} + 2(\dfrac{\theta}{\varphi^2} + \theta)p_{2n} \\ +\dfrac{[2(1-\mu) - \varphi]\delta a + \varphi\delta^2 c}{\varphi^2\delta} \\ +(1-\mu)a - \theta c + \delta(c-s) + (\dfrac{\delta}{\varphi} - \theta)e_1 w \\ +\delta e_2 w = 0 \end{cases}$$

By solving it, we have

$$\begin{cases} p_{2n} = \dfrac{\mu\delta^3 a + (1-\mu)\delta^2\theta a + \delta^4 c - \delta^2\theta^2 c}{2(\delta^4 - \delta^2\theta^2)} + \dfrac{e_1 w}{2} \\ p_{2r} = \dfrac{(\varphi^2+\varphi^4)\mu\delta^2\theta a + (1-\mu)(\varphi^2\theta^2 + \varphi^4\delta^2)\delta a}{2(\varphi^2+\varphi^4)(\delta^4-\delta^2\theta^2)} \\ + \dfrac{2(1-\mu)\varphi^2\delta a - \varphi^3\delta a}{2(\varphi^2+\varphi^4)\delta^2} + \dfrac{\varphi^3\delta^2 c + \varphi^2\delta\theta c + \varphi^4\delta^2(c-s)}{2(\varphi^2+\varphi^4)\delta^2} \\ + \dfrac{(\varphi^2\delta\theta + \varphi^3\delta^2)e_1 w + \varphi^4\delta^2 e_2 w}{2(\varphi^2+\varphi^4)\delta^2} \end{cases} \tag{13}$$

The Hessianmatrix of π_m is still H_2, which is negative definite. Thus, (13) is the unique extreme point of π_m.

It is shown by (13) that p_{2r} relates to both e_1 and e_2, which is quite different from (9). Apparently, this relation is due to the constraint with respect to the collection rate. Actually, p_1 also relates to both e_1 and e_2, because

$$p_1 = \frac{a}{\delta} - \frac{(1-\mu)a - \delta p_{2r} + \theta p_{2n}}{\varphi\delta}.$$

Because the expression of each sales quantity is complex, we show them as follows, separately, as shown in the equation at the bottom of the next page, and

$$q_{2r} = \frac{(1-\mu)\varphi^2\delta^2 a + \varphi\delta^2 a - \varphi\delta^3 c + \varphi^2\delta^2\theta c - \varphi^2\delta^3(c-s)}{2(1+\varphi^2)\delta^2} - \frac{(\varphi\delta - \varphi^2\theta)e_1 w + \varphi^2\delta e_2 w}{2(1+\varphi^2)}.$$

In order to be concise, we denote

$$q_1 = T_1 - \frac{(\delta - \varphi\theta)e_1 w + \varphi\delta e_2 w}{2(1+\varphi^2)}, \tag{14}$$

$$q_{2n} = T_2 - \frac{\delta e_1 w}{2} + \frac{(\delta\theta^2 + \varphi\delta^2\theta)e_1 w + \varphi^2\delta^2\theta e_2 w}{2(1+\varphi^2)\delta^2}, \tag{15}$$

$$q_{2r} = T_3 - \frac{(\varphi\delta - \varphi^2\theta)e_1 w + \varphi^2\delta e_2 w}{2(1+\varphi^2)}. \tag{16}$$

Then we have

$$\begin{aligned} \pi_s = [T_1 + T_2 - \frac{\delta e_1 w}{2} \\ + \frac{(\delta\theta^2 + \varphi\delta^2\theta)e_1 w + \varphi^2\delta^2\theta e_2 w}{2(1+\varphi^2)\delta^2}]e_1 w - Lw \\ - \frac{(\delta - \varphi\theta)e_1^2 w^2 + \varphi\delta e_1 e_2 w^2}{2(1+\varphi^2)} \\ + [T_3 - \frac{(\varphi\delta - \varphi^2\theta)e_1 w + \varphi^2\delta e_2 w}{2(1+\varphi^2)}]e_2 w. \end{aligned}$$

It can be arranged in descending order:

$$\begin{aligned} \pi_s = (\frac{(\delta\theta^2 + \varphi\delta^2\theta)e_1^2 + \varphi^2\delta^2\theta e_1 e_2}{2(1+\varphi^2)\delta^2} \\ - \frac{(\delta - \varphi\theta)e_1^2 + \varphi\delta e_1 e_2}{2(1+\varphi^2)} \\ - \frac{\delta e_1^2}{2} - \frac{(\varphi\delta - \varphi^2\theta)e_1 e_2 + \varphi^2\delta e_2^2}{2(1+\varphi^2)})w^2 \\ + (T_1 e_1 + T_2 e_1 + T_3 e_2 - L)w. \end{aligned}$$

The unique solution of max π_s is obtained as follows, (17), as shown at the bottom of the next page.

According to the above analysis, for any given w, q_e is determined. Given that w determined by (17) is the unique solution of max π_s under q_e, we have the following conclusion:

Proposition 3: $w > 0$ under $q_e > 0$.

Under Proposition 3, we only need to observe the change of q_e. There are two possible regions for model (12):

a. Case 2.2. In this situation, (3) holds, (4) doesn't hold, and

$$(q_1 + q_{2n})e_1 + q_{2r}e_2 > L$$

under (6). By dealing with (14), (15) and (16) under (17), $q_e < 0$ is equivalent to, as shown in the equation at the bottom of the next page, which is mutually exclusive with (3). Thus, $q_e < 0$ in this region is impossible.

b. (3) doesn't hold and $\varphi q_1 < q_{2r}$ under (9) and (11). By comparing (3) and the carbon emission $(q_e + L)$ in this

$$\begin{aligned} \pi_s = -\frac{(2\delta e_1^2 - 2\theta e_1 e_2 + \delta e_2^2)}{2}w^2 \\ + [\frac{(1+\mu)ae_1 + (1-\mu)ae_2 - 2\delta c e_1 - \delta(c-s)e_2 + \theta(c-s)e_1 + \theta c e_2}{2} - L]w. \end{aligned}$$

$$\begin{aligned} \pi_m = \frac{[\varphi a - (1-\mu)a + \delta p_{2r} - \theta p_{2n} - \varphi\delta c][(1-\mu)a - \delta p_{2r} + \theta p_{2n}]}{\varphi^2\delta} \\ + (p_{2n} - c)(\mu a - \delta p_{2n} + \theta p_{2r}) + (p_{2r} - c + s)[(1-\mu)a - \delta p_{2r} + \theta p_{2n}] \\ - w[(\mu a - \delta p_{2n} + \theta p_{2r})e_1 + (\frac{e_1}{\varphi} + e_2)((1-\mu)a - \delta p_{2r} + \theta p_{2n})]. \end{aligned}$$

situation, we have

$$\frac{[(1+\mu)a-2\delta c+\theta(c-s)]e_1}{2}+\frac{[(1-\mu)a-\delta(c-s)+\theta c]e_2}{2}-(q_e+L)=\frac{(2\delta e_1{}^2+\delta e_2{}^2-2\theta e_1e_2)[(\theta+\delta\varphi)e_1-\delta e_2]}{H}\times[(\varphi+\mu-1)a-(\theta+\delta\varphi-\delta)c-\delta s], \quad (18)$$

where

$$H=[\theta^2+2\delta\theta\varphi+\delta^2(2+3\varphi^2)]e_1{}^2+\delta^2(2+\varphi^2)]e_2{}^2-2\delta[\delta\varphi+\theta(2+\varphi^2)]e_1e_2.$$

We substitute (9) and (11) into $\varphi q_1<q_{2r}$ and then obtain

$$\frac{H_1e_1{}^2+H_2e_2{}^2-H_3e_1e_2}{2(\theta+\delta\varphi)e_1-2\delta e_2}>L,$$

where

$$H_1=[\theta(1+\mu)+\delta(4-4\mu+\mu\varphi-3\varphi)]a+(4\delta^2-\theta^2-\varphi\delta\theta)s+[\theta^2+\delta\theta(2+\varphi)-(4-2\varphi)\delta^2]c,$$
$$H_2=\delta[\delta s+(2\delta\varphi+\theta-\delta)c-(2\varphi+\mu-1)a],$$

and

$$H_3=3\theta^2c+\theta a(3-3\mu-4\varphi)-\delta^2(2-\varphi)c+\delta\theta(3\varphi-2)c+\delta(2\theta-\delta\varphi)s+\delta a(1+\mu+\mu\varphi-1).$$

By comparing the above result and $(qe+L)$, we have

$$\frac{H_1e_1{}^2+H_2e_2{}^2-H_3e_1e_2}{2(\theta+\delta\varphi)e_1-2\delta e_2}-(q_e+L)=\frac{(2\delta e_1{}^2+\delta e_2{}^2-2\theta e_1e_2)^2}{H[(\theta+\delta\varphi)e_1-\delta e_2]}\times\delta(1+\varphi^2)[\delta s+(\theta+\delta\varphi-\delta)c-(\varphi+\mu-1)a]. \quad (19)$$

By analyzing (18) and (19), we find that (3) doesn't hold, $\varphi q_1<q_{2r}$ under (9) and (11), and $q_e+L\leq L$ can hardly occur at the same time. Thus, $q_e<0$ in this region is also impossible.

According to the above results, we draw the following conclusion:

Proposition 4: The four decision models constructed in Section IV and Section V compose a complete decision process for the manufacturer.

Moreover, according to (11) and (17), the value of w will be larger when the market demand expands.

VI. NUMERICAL STUDY

In this section, we investigate the impact of the carbon cap and the collection ratio on the decision strategy of the manufacturer. In particular, the two-sidedness of the collection ratio is examined.

The general parameters used throughout this section are presented as follows: the potential market demand of each sales period $a=2000$, the linear price-sensitive coefficient $\delta=2$, the price substitution coefficient $\theta=1$, the preference proportion for the new product $\mu=0.6$, the production cost $c=200$, the cost saving $s=100$, the carbon

$$q_1=\frac{(1-\mu)\varphi\delta^2a+\delta^2a-\delta^3c+\varphi\delta^2\theta c-\varphi\delta^3(c-s)}{2(1+\varphi^2)\delta^2}-\frac{(\delta-\varphi\theta)e_1w+\varphi\delta e_2w}{2(1+\varphi^2)},$$
$$q_{2n}=\frac{\mu(1+\varphi^2)\delta^2a+(1-\mu)\delta\theta a-\varphi\delta\theta a}{2(1+\varphi^2)\delta^2}+\frac{(\delta\theta^2+\varphi\delta^2\theta)e_1w}{2(1+\varphi^2)\delta^2}-\frac{\delta e_1w}{2}+\frac{\varphi^2\delta^2\theta e_2w+\varphi\delta^2\theta c+\delta\theta^2c-(1+\varphi^2)\delta^3c+\varphi^2\delta^2\theta(c-s)}{2(1+\varphi^2)\delta^2},$$

$$w=\frac{T_1e_1+T_2e_1+T_3e_2-L}{2[(2\delta^3-2\varphi\delta^2\theta)(e_1{}^2+\varphi e_1e_2)-\delta\theta^2e_1{}^2+\varphi^2\delta^3(e_1{}^2+e_2{}^2)]}. \quad (17)$$

$$\frac{[1+(1-\mu)\varphi+\mu(1+\varphi^2)]\delta^2ae_1+(1-\mu-\varphi)\delta\theta ae_1}{2(1+\varphi^2)\delta^2}-\frac{[\delta^3-2\varphi\delta^2\theta-\delta\theta^2+(1+\varphi^2)\delta^3]ce_1}{2(1+\varphi^2)\delta^2}-\frac{(\varphi\delta^3-\varphi^2\delta^2\theta)(c-s)e_1}{2(1+\varphi^2)\delta^2}+\frac{[(1-\mu)\varphi^2\delta^2a+\varphi\delta^2a-\varphi\delta^3c+\varphi^2\delta^2\theta c-\varphi^2\delta^3(c-s)]e_2}{2(1+\varphi^2)\delta^2}>L,$$

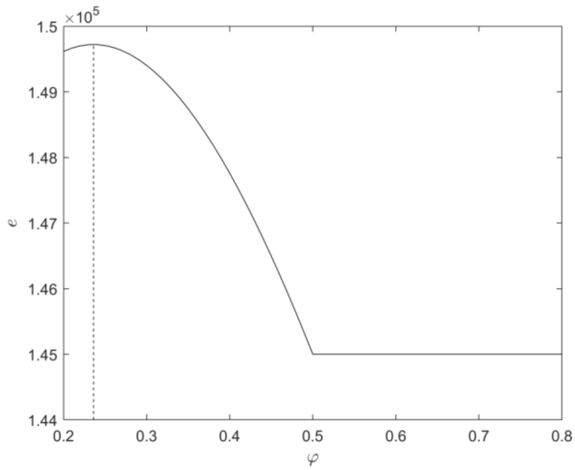

FIGURE 1. The change of the carbon emission.

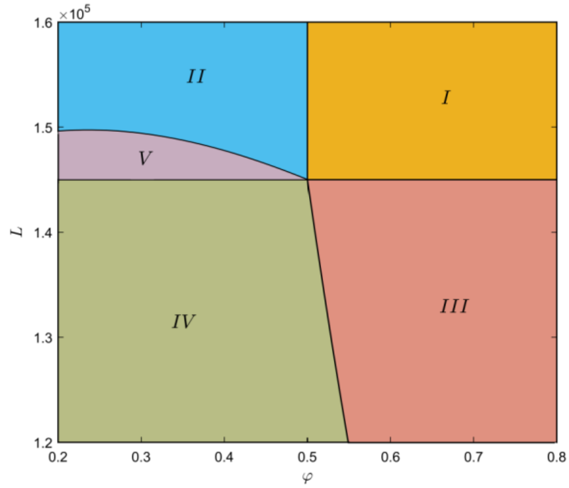

FIGURE 2. Feasible region of each situation.

emission for producing a new product $e_1 = 100$, and the carbon emission for producing a remanufactured product $e_2 = 50$. Some parameters refer to [24] and [25].

First, without considering the carbon cap, we analyze the two-sidedness of the collection ratio by giving $\varphi \in [0.2, 0.8]$. According to (4), the collection ratio is not an effective factor when $\varphi \geq 0.5$, and the carbon emission is 145000. When $\varphi < 0.5$, the carbon emission is

$$\frac{520000\varphi^2 + 320000\varphi + 1160000}{8(1+\varphi^2)}.$$

According to the above results, we depict the following curve for the change of the carbon emission:

In Fig. 1, the two-sidedness of the collection ratio is revealed. With the decrease of φ, the carbon emission may increase or decrease. Hence, Suppose 1 is verified. When φ decreases and the carbon emission increases, it means the manufacturer enhances the sales of the new product by pricing strategies.

Next, we examine the different decision of the manufacturer under $\varphi \in [0.2, 0.8]$ and $L \in [120000, 160000]$. Region I is defined by $L \geq 145000$ and $\varphi \geq 0.5$. Region II is defined by $L \geq 145000$, $\varphi < 0.5$, and

$$\frac{520000\varphi^2 + 320000\varphi + 1160000}{8(1+\varphi^2)} \leqslant L.$$

Region III is defined by $L < 145000$ and

$$\varphi(270000 + 2L) \geqslant 280000.$$

Region IV is defined by $L < 145000$,

$$\varphi(270000 + 2L) < 280000,$$

and

$$\frac{65000\varphi^2 + 40000\varphi + 145000 - 7500\varphi^2 w - 17500w}{1+\varphi^2} > L,$$

where

$$w = \frac{65000\varphi^2 + 40000\varphi + 145000 - (1+\varphi^2)L}{(1+\varphi^2)(120000\varphi^2 + 280000)}.$$

Region V is defined by $L \geq 145000$, $\varphi < 0.5$,

$$\frac{520000\varphi^2 + 320000\varphi + 1160000}{8(1+\varphi^2)} > L,$$

and

$$\frac{65000\varphi^2 + 40000\varphi + 145000 - 7500\varphi^2 w - 17500w}{1+\varphi^2} > L.$$

According to the above results, we draw the following figure:

In Fig. 2, region I and region II represent the decision area where the carbon cap is high enough and carbon trade is unnecessary. The others, region III, region IV and region V, represent the decision area where carbon trade is necessary.

VII. CONCLUSION

This paper studies optimal pricing decisions in a hybrid manufacturing–remanufacturing system in the presence of cap-and-trade mechanism. A manufacturer and a carbon-trade supplier are involved in our discussion. The manufacturer decides whether carbon trade is needed or not, with the purpose of maximizing his revenue. When carbon trade occurs, the manufacturer and the carbon-trade supplier conduct a Stackelberg game.

As the crucial influence factors of pricing decisions, carbon cap and collection ratio are paid close attention to. We show that the impact of the collection ratio for the carbon emission is two-sided. When the collection ratio is higher than a certain threshold value, the carbon emission reduces with the increase of the collection ratio. Carbon cap is another crucial factor, which determines whether carbon trade occurs or doesn't occur.

From the manufacturer's perspective, the results presented in this study provide a complete decision scheme for any situation. Enhancing the collection ratio may be an effective approach to low the carbon emission. From the government's perspective, laying out an appropriate carbon cap is of significance for the production promotion of remanufactured product and the reduction of carbon emission.

For future research, it is worthwhile to consider the following two aspects: (a) the develop of green technology; and (b) the participation of the government and retailers. In practice, problems will be more complex when considering the above aspects.

REFERENCES

[1] C. Wang, W. Wang, and R. Huang, "Supply chain enterprise operations and government carbon tax decisions considering carbon emissions," *J. Cleaner Prod.*, vol. 152, pp. 271–280, May 2017.

[2] Q. Chai, Z. Xiao, K.-H. Lai, and G. Zhou, "Can carbon cap and trade mechanism be beneficial for remanufacturing?" *Int. J. Prod. Econ.*, vol. 203, pp. 311–321, Sep. 2018.

[3] A. Yenipazarli, "Managing new and remanufactured products to mitigate environmental damage under emissions regulation," *Eur. J. Oper. Res.*, vol. 249, no. 1, pp. 117–130, Feb. 2016.

[4] Y. Wang, W. Chen, and B. Liu, "Manufacturing/remanufacturing decisions for a capital-constrained manufacturer considering carbon emission cap and trade," *J. Cleaner Prod.*, vol. 140, pp. 1118–1128, Jan. 2017.

[5] X. Chang, H. Xia, H. Zhu, T. Fan, and H. Zhao, "Production decisions in a hybrid manufacturing–remanufacturing system with carbon cap and trade mechanism," *Int. J. Prod. Econ.*, vol. 162, pp. 160–173, Apr. 2015.

[6] T. Shu, Q. Wu, S. Chen, S. Wang, K. K. Lai, and H. Yang, "Manufacturers'/remanufacturers' inventory control strategies with cap-and-trade regulation," *J. Cleaner Prod.*, vol. 159, pp. 11–25, Aug. 2017.

[7] S.-S. Gan, I. N. Pujawan, and B. Widodo, "Pricing decision for new and remanufactured product in a closed-loop supply chain with separate sales-channel," *Int. J. Prod. Econ.*, vol. 190, pp. 120–132, Aug. 2017.

[8] L. Yang, Y. Hu, and L. Huang, "Collecting mode selection in a remanufacturing supply chain under cap-and-trade regulation," *Eur. J. Oper. Res.*, vol. 287, no. 2, pp. 480–496, Dec. 2020.

[9] P. Zhao, Q. Deng, J. Zhou, W. Han, G. Gong, and C. Jiang, "Optimal production decisions for remanufacturing end-of-life products under quality uncertainty and a carbon cap-and-trade policy," *Comput. Ind. Eng.*, vol. 162, Dec. 2021, Art. no. 107646.

[10] X. Xu, X. Xu, and P. He, "Joint production and pricing decisions for multiple products with cap-and-trade and carbon tax regulations," *J. Cleaner Prod.*, vol. 112, pp. 4093–4106, Jan. 2016.

[11] B. Liu, M. Holmbom, A. Segerstedt, and W. Chen, "Effects of carbon emission regulations on remanufacturing decisions with limited information of demand distribution," *Int. J. Prod. Res.*, vol. 53, no. 2, pp. 532–548, Jan. 2015.

[12] P. He, W. Zhang, X. Xu, and Y. Bian, "Production lot-sizing and carbon emissions under cap-and-trade and carbon tax regulations," *J. Cleaner Prod.*, vol. 103, pp. 241–248, Sep. 2015.

[13] K. Cao, P. He, and Z. Liu, "Production and pricing decisions in a dual-channel supply chain under remanufacturing subsidy policy and carbon tax policy," *J. Oper. Res. Soc.*, vol. 71, no. 8, pp. 1199–1215, Aug. 2020.

[14] S. Kushwaha, A. Ghosh, and A. K. Rao, "Collection activity channels selection in a reverse supply chain under a carbon cap-and-trade regulation," *J. Cleaner Prod.*, vol. 260, Jul. 2020, Art. no. 121034.

[15] G. Ferrer and J. M. Swaminathan, "Managing new and remanufactured products," *Manage. Sci.*, vol. 52, no. 1, pp. 15–26, Jan. 2006.

[16] C.-H. Wu, "Product-design and pricing strategies with remanufacturing," *Eur. J. Oper. Res.*, vol. 222, no. 2, pp. 204–215, Oct. 2012.

[17] X. Wang, Y. Zhu, H. Sun, and F. Jia, "Production decisions of new and remanufactured products: Implications for low carbon emission economy," *J. Cleaner Prod.*, vol. 171, pp. 1225–1243, Jan. 2018.

[18] G. Dou, H. Guo, Q. Zhang, and X. Li, "A two-period carbon tax regulation for manufacturing and remanufacturing production planning," *Comput. Ind. Eng.*, vol. 128, pp. 502–513, Feb. 2019.

[19] M. Alegoz, O. Kaya, and Z. P. Bayindir, "A comparison of pure manufacturing and hybrid manufacturing–remanufacturing systems under carbon tax policy," *Eur. J. Oper. Res.*, vol. 294, no. 1, pp. 161–173, Oct. 2021.

[20] A. Atasu, M. Sarvary, and L. N. Van Wassenhove, "Remanufacturing as a marketing strategy," *Manage. Sci.*, vol. 54, no. 10, pp. 1731–1746, Oct. 2008.

[21] J. D. Abbey, J. D. Blackburn, and V. D. R. Guide, "Optimal pricing for new and remanufactured products," *J. Operations Manage.*, vol. 36, no. 1, pp. 130–146, May 2015.

[22] W. Gan, L. Peng, D. Li, L. Han, and C. Zhang, "A coordinated revenue-sharing-based pricing decision model for remanufactured products in carbon cap and trade regulated closed-loop supply chain," *IEEE Access*, vol. 7, pp. 142879–142893, 2019.

[23] X. Zhu and M. Wang, "Optimal pricing strategy of a hybrid trade old for new and remanufactured products supply chain," *Optim. Lett.*, vol. 15, no. 2, pp. 495–511, Mar. 2021.

[24] X. Zhang, Z. Lou, Z. Sun, and X. Dai, "Pricing and investment decision issues of an automobile manufacturer for different types of vehicles," *IEEE Access*, vol. 9, pp. 73083–73089, 2021.

[25] X. Chang, Y. Li, Y. Zhao, W. Liu, and J. Wu, "Effects of carbon permits allocation methods on remanufacturing production decisions," *J. Cleaner Prod.*, vol. 152, pp. 281–294, May 2017.

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