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Research article

Which is better for remanufacturing: carbon asset pledge financing vs equity financing?

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Abstract: The development of the low-carbon economy has prompted many manufacturing enterprises to choose the remanufacturing mode with a low cost and low carbon emission characteristics. Due to the larger amount of capital investment for remanufacturing, many remanufacturing enterprises are often faced with insufficient funding, and the remanufacturer needs to seek a suitable financing pattern to obtain financial support. In this sense, we consider a monopoly remanufacturer and compare the optimal operational decision under two financing methods, i.e., carbon asset pledge financing (CAPF) and equity financing (EF). We find that whether the remanufacturer adopts EF or CAPF is determined by the dividend ratio or their initial capital, and only when the dividend ratio or their initial capital meets a certain condition can it benefit from the EF or CAPF. Compared with the scenario of capital constraint without financing, the adoption of CAPF or EF can always increase the volume of new products, consumer surplus, and environmental impact. For underfunded remanufacturers, adopting CAPF is more favorable than the production of remanufactured products than EF; however, the EF always has a higher contribution rate to consumer surplus and environmental impact than the CAPF. Only when the dividend ratio is in the appropriate range can the remanufacturer obtain the most profit; otherwise adopting the CAPF is more profitable.

Keywords: remanufacturing; carbon asset pledge financing; equity financing; operational decision

Mathematics Subject Classification: 58F15, 58F17, 53C35

1. Introduction

Carbon trading markets serve as critical mechanisms for climate change mitigation, efficiently allocating emission resources to reduce carbon footprints [1, 2]. However, in energy-intensive industries

like steel and construction machinery, carbon emissions remain high due to the nature of the industry. Against this backdrop, remanufacturing has gained significant attention from manufacturing enterprises. Its economic advantages and low-carbon production characteristics make it an attractive choice. Many enterprises have adopted the remanufacturing production mode, which is characterized by low costs and low carbon emissions, to align with the demands of sustainable development [3]. Considering that the remanufacturing involves recycling, classification, disassembly, and many other links, each link requires a large amount of investment, which means that many remanufacturers often run out of funds in the manufacturing/remanufacturing process. This not only impedes the development of remanufacturing but also leads to bankruptcy. Therefore, how to solve the problem of lack of funds has become an urgent problem for remanufacturers [4].

The existing literature has explored the issue of funding constraints in the production and operation of remanufacturing enterprises. Some studies have examined the impact of bank loans and trade credit on remanufacturing operations. However, limited research has focused on the application of carbon asset pledge financing (CAPF) in remanufacturing operations management. CAPF, as a new mortgage loan model, can revitalize the carbon assets of enterprises and effectively solve the problem of enterprises' shortages [5]. In recent years, an increasing number of enterprises have obtained loans through CAPF. For example, Hubei Yihua Group and Hubei Chuxing Chemical Co., Ltd. jointly obtained a CNY 600 million carbon emission rights pledge loan from the Hubei Branch of the Export-Import Bank of China in 2023. Nanjing Iron and Steel Co. Ltd. obtained a CNY 100 million carbon emission rights pledge loan from the Nanjing Branch of China Citic Bank in 2024.

For financially constrained remanufacturers, obtaining loans from financial institutions is challenging due to factors such as low credit levels or lack of collateral. As a result, some enterprises have turned to equity financing (EF) to address funding shortages. With the development of the low-carbon economy, the business environment for remanufacturers has changed significantly. Especially for remanufacturers producing carbon-dependent products, such as Caterpillar, Xugong Group, and Sany Group, the carbon market and trading mechanism offer new opportunities. These enterprises can pledge carbon assets to financial institutions to apply for CAPF loans, which not only revitalizes idle carbon assets but also provides a solution to funding shortages.

This study focuses on emission-dependent remanufacturers that simultaneously produce and sell products. By introducing CAPF and EF into remanufacturing production and operations management, this paper seeks to address the following research questions.

(1) How should the conditions for adopting EF and CAPF be defined for financially constrained and emissions-dependent remanufacturers?

(2) Are CAPF and EF beneficial to remanufacturing compared with the situation of capital constraint and no financing?

(3) Compared with EF, is CAPF still beneficial for reducing carbon emissions and improving the profit of remanufacturers?

The primary objective of this research is to explore the applicability of CAPF and EF in the context of remanufacturing enterprises. Specifically, this study aims to define the boundary conditions for adopting EF and CAPF for financially constrained remanufacturers. It seeks to analyze the effects of these two financing methods on the environment, consumer surplus, and profitability of remanufacturers. Additionally, this research aims to provide management insights for capital-constrained remanufacturers, helping them make informed financing decisions. The contributions of this paper are threefold. First, we

introduce the CAPF and EF into the remanufacturing operation and defines the boundary conditions of EF and CAPF for capital-constrained remanufacturers. Second, the paper studies the optimal production decision of remanufacturers under the EF and the CAPF, and analyzes the effects of these financing methods on the environment, consumer surplus, profit, etc., providing management insights for capital-constrained remanufacturers. Third, we propose the concept of the financing contribution rate and provide a quantitative solution of the two financing methods for remanufacturers, enriching the theory of remanufacturing operation management.

The rest of our work is organized as follows: We review the relevant literature in Section 2. Section 3 presents the model's description and assumptions. We develop the benchmark model, the CAPF model, and the EF model in Section 4 and analyze the optimal equilibrium solution of the three different models mentioned above. We present a comparative analysis of the optimal equilibrium solution through numerical examples in Section 5. Section 6 concludes the paper.

2. Literature review

This section reviews the relevant literature and divides it into three streams as follows: (i) Operational decisions in remanufacturing; (ii) CAPF; (iii) EF in operations management.

2.1. Operational decisions in remanufacturing

As a sustainable green production mode, remanufacturing has attracted significant attention from governments and enterprises, prompting many countries to enact policies promoting its adoption [6, 7]. Extensive literature has examined remanufacturing-related operational decisions from diverse perspectives, including recycling channel selection [8–10], government regulations and subsidies [11–14], remanufactured products' process design [15–17], and carbon trading and carbon policy [18, 19]. Recent studies have also incorporated behavioral factors such as risk aversion and fairness concerns into remanufacturing decisions [20–22].

However, a critical limitation of this literature is its predominant assumption that remanufacturers are financially unconstrained. In fact, remanufacturing involves capital-intensive processes, each requiring substantial investment, often exceeding firms' internal funds [4]. Although some studies have begun to address capital constraints through trade credit or bank financing [23–25], they have largely overlooked two important developments: (i) The emergence of carbon assets as a new form of collateral under carbon trading systems, and (ii) the availability of EF as an alternative to debt-based mechanisms. Therefore, this paper considers a capital-constrained remanufacturer and investigates the remanufacturer's production decision under CAPF and EF.

2.2. Carbon asset pledge financing

As carbon trading systems expand globally, carbon assets have emerged as a new class of financial instruments [1, 26]. Chevallier [27] established that carbon emission permits, carbon options, and related derivatives constitute valuable corporate assets. Subsequent research has focused on carbon asset valuation and risk assessment [28], carbon management systems [29, 30], and value creation mechanisms through carbon assets [31, 32].

CAPF, where firms pledge carbon emission allowances as collateral to obtain loans, has gained traction in practice, and many scholars have conducted research from various perspectives on the impact

of CAPF on the operations of enterprises. Cao and Yu [33] constructed a supply chain (SC) including a capital-constrained manufacturer and investigated the optimal selection of SC members under CAPF. Fu et al. [4] investigated the rent-seeking behavior among firms, banks, and evaluation agencies in CAPF and found that the penalty mechanism can reduce the occurrence of rent-seeking behavior in CAPF. More recently, Fu and Wang [34] proposed hybrid CAPF models combining carbon asset pledges with bank loans for authorized remanufacturing firms. Xu et al. [35] compared platform financing with bank financing for green manufacturing systems, showing that the choice depends on the correlation between market size and carbon permit prices.

Despite these advances, the literature on CAPF suffers from several gaps. First, most studies examine CAPF in isolation, without a systematic comparison with other financing instruments. Second, the unique context of remanufacturing with its dual production (new and remanufactured products) and emission reduction potential has received limited attention. Third, the comparative effectiveness of CAPF versus EF remains unexplored.

To address the first gap, we extend our review to other green financing mechanisms. Table 1 provides a systematic comparison.

Table 1. Comparison of green financing instruments for remanufacturing.

Financing instrument	Collateral	Cost structure	Suitability for remanufacturers	References
Bank loans	Physical assets, credit history	Fixed interest rate	Established firms with tangible assets	[9, 23]
Trade credit	Purchase orders, relationships	Early payment discounts	Firms with strong supplier relationships	[32]
Government subsidies	None	Zero	Firms meeting policy criteria	[11]
Platform financing	Carbon permits, sales data	Commission + interest	Firms selling through online platforms	[35]
CAPF	Carbon emission allowances	Interest rate	Emission-dependent firms	[5, 33]
EF	Equity stake	Dividend ratio	Firms with growth potential but limited collateral	[7, 36]

This comparison reveals that CAPF leverages the carbon assets that remanufacturers inherently possess, aligns incentives for reducing emissions, and provides an alternative for firms lacking traditional collateral. However, its comparative advantages and disadvantages relative to EF, particularly for remanufacturers with different carbon asset endowments, remain unexamined.

2.3. EF in operations management

EF, where firms raise capital by selling ownership stakes, has been extensively studied in corporate finance but has only recently been integrated into operations management research [37, 38]. At the firm level, studies have examined how credit policies affect the cost of equity [36], how digital transformation

influences equity financing costs [39], and how blockchain adoption affects EF [40]. Chen [41] found that green product innovation attracts equity investors and reduces financing costs.

In operations management, EF has been incorporated into supply chain models [42]. Li et al. [37] showed that EF improves supply chains' performance. He et al. [9] compared EF and debt financing for capital-constrained supply chains, finding that the optimal choice depends on the retailer's initial capital. Su et al. [43] demonstrated that combining EF with debt financing reduces risk and increases profits. Liu et al. [44] examined EF alongside manufacturer financing and subsidy-based delayed financing, showing that EF adoption depends on dividend ratios.

Table 2. Comparison with existing studies.

Paper	Capital constraints	CAPF	EF	Objectives	Decision variables	Limitations
[7]				Maximization of profits	Output	Without funding constraints
[19]				Maximization of profits	Prices	Without funding constraints
[22]	√			Remanufacturing mode selection	Prices	Without CAPF
[32]	√	√		Maximization of profits	Output	Without CAPF
[33]	√	√		Maximization of profits	Prices	Without EF
[5]	√	√		Maximization of profits	Output	Without EF
[38]	√		√	Maximization of profits	Prices	Without CAPF
[39]			√	Maximization of profits	Prices	Without CAPF
[40]	√		√	Maximization of profits	Output	Without CAPF
This paper	√	√	√	Maximization of profits	Output	

The abovementioned literature has examined the performance of EF in operations management. However, they have three notable limitations. First, EF studies typically focus on manufacturers or retailers generally, without considering the specific context of remanufacturing. Second, the interaction between EF and carbon asset management, which is particularly relevant for remanufacturers, has been ignored. Third, most critically for our study, no research has systematically compared EF with CAPF for remanufacturing operations.

Synthesizing the three literature streams reveals a clear research gap: No existing study compares the effectiveness of CAPF versus EF for capital-constrained remanufacturers operating under carbon

trading systems. Table 2 maps the positioning of our study against the existing literature, highlighting this gap.

By comparison with the existing literature, Tables 1 and 2 presents the distinctions between this study and previous works. We observe that while prior studies have individually examined CAPF, EF, and remanufacturing operations, the research on CAPF and EF has primarily focused on micro-level operations, such as system development, patterns, and corporate financing. Although some literature has considered the impact of financial constraints on remanufacturing operations, the current low-carbon economic development has altered the financing environment for remanufacturers. Remanufacturing enterprises can utilize EF or the emerging low-carbon financing instrument of CAPF to alleviate capital shortages. However, the comparative advantages of CAPF over traditional EF, as well as its potential benefits for remanufacturing operations, remain unresolved questions. Therefore, this study introduces both CAPF and EF into remanufacturing operations management and investigates the impacts of these two distinct financing methods on the operations of remanufacturers. Furthermore, we propose the concept of the financing contribution rate and develop a quantitative model to evaluate the financing effectiveness of these two models. This work seeks to provide a theoretical foundation for formulating optimal financing strategies for remanufacturers in a low-carbon environment.

3. Model formulation

3.1. Model description

We consider a monopoly remanufacturer that produces both new and remanufactured products. The remanufacturer operates under a cap-and-trade system, receives an initial carbon emission allowance, and can trade emission permits in the carbon market. Due to the capital-intensive nature of remanufacturing (collection, disassembly, remanufacturing), the firm may face a capital constraint. To finance production, the remanufacturer can either (i) pledge its carbon assets to obtain a loan from a bank (CAPF) or (ii) raise funds from investors by selling an equity stake (EF). The operating process of CAPF and EF is shown in Figure 1 and Figure 2.
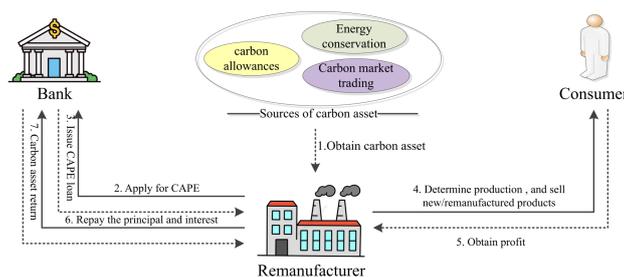

Figure 1. The operation process of CAPF.

Figure 2. The operation process of EF.

3.2. Notation

All key parameters and economic interpretations are shown in Table 3.

Table 3. Notations.

Symbol	Description	Economic interpretation
	Decision variables	
q_i	Production quantity of new/remanufactured products, $i = n, r$	Determine revenue, cost, emissions, and financing needs
θ	Carbon asset pledge rate	Higher θ means a larger loan amount but more carbon assets are tied up
	Parameterss	
η	Consumers' preference level for remanufactured product	Higher η increases demand for remanufactured products
p_i	Price of new/remanufactured products	Endogenously determined by inverse demand functions; captures price discrimination
c_i	Cost of new/remanufactured product	$c_n < c_r$ due to material and energy savings in remanufacturing
p_e	The carbon trading price	Determines cost/revenue from carbon trading
e_i	Unit of emissions of new/remanufactured products	$e_r = \beta e_n$; β represents the emission reduction efficiency of remanufacturing
t	Emission price volatility	Captures uncertainty in the carbon market
r	Interest rate of CAPF loans	Cost of debt financing
T	Pledge period of CAPF loans	Loan duration
α	EF dividend ratio	Fraction of profits paid to equity investors
B	Initial capital	Firm's own financial resources
ε	The coefficient of carbon assets	Reflects the stringency of the emissions cap
L^j	The remanufacturer's carbon asset in Model j, $j = N, S, CF, EF$	Allowances allocated by the regulator
E^j	Actual carbon emissions in Model j, $j = N, S, CF, EF$	Measures the environmental impact of remanufacturers
CS^j	The consumer surplus in in Model j, $j = N, S, CF, EF$	Measures welfare from product consumption
π_m^j	The remanufacturer's profit in Model j, $j = N, S, CF, EF$	Net revenue minus production cost, carbon trading, and financing costs
π_i	The profit of banks and investors, $i = b, e$, where N denotes banks and S denotes investors.	Financial intermediaries' profits

3.3. Assumptions

(1) According to Caterpillar, Sany Group, Doosan Group, we know that these remanufacturers use an ordering system to produce remanufactured products. This operational model is widely implemented in practice, as evidenced by leading firms such as Caterpillar, Sany Group, and Doosan Group [45]. Therefore, we assume that all end-of-life products can be remanufactured and had remanufactured products have only one manufacturing cycle, which can simplify the dynamics aspects. We set the costs and unit emissions of new/remanufactured products as $C_n, C_r, e_n, e_r (e_r = \beta e_n)$, although this setting ignores economics of scale, though it is common in analytical operations models.

(2) We assume that the production quantities of new and remanufactured products are q_n and q_r, respectively. The carbon footprint has been widely recognized in the literature as a key metric for

evaluating environmental performance. In line with An et al. [23], we quantify environmental impact with total carbon emissions. Specifically, under various manufacturing and remanufacturing scenarios, the environmental impact is denoted as $E^j = e_n(q_n^j + \beta q_r^j)$. The demand functions for the two product types are denoted as $p_n = 1 - q_n - \delta q_r$, and $p_r = \delta(1 - q_n - \delta q_r)$, which is consistent with Ferrer and Swaminathan [46]. This standard formulation captures the substitution between new and remanufactured products through the parameter δ and ensures analytical tractability.

(3) We assume that the pledge rate of CAPF loan is θ, the interest rate of CAPF loans is r, the pledge period is T, the carbon price for the final period of carbon trading is $p_e(1 + t)$, and the remanufacturer needs to repay $p_e \theta L^{CF} e^{rT}$ to banks to redeem their carbon asset. Meanwhile, referring to Xia et al. [22], the proportion of dividends to investors in EF of remanufacturers is α . All agents (the remanufacturer, the bank, investors) maximize expected profit and are risk-neutral.

(4) On the basis of the cases of enterprises implementing CAPF and the actual situation of banks conducting CAPF business, we observe that firms' carbon assets consist primarily of government-allocated allowances. The carbon assets of firms are mainly carbon allowances, and the EU, the United States, and China all adopt the historical emission method and other methods to allocate carbon allowances to enterprises. Therefore, according to Chang et al. [47], assuming that the remanufacturer's carbon asset is L, $L = \epsilon E (0 < \epsilon < 1)$ and that the adopted carbon asset's valuation is reasonable and consistent with the findings reported in Fu et al. [5] . In addition, since the carbon assets of the remanufacturer are easily regulated during the pledge process, defaulting on CAPF is not considered.

4. Model formulation

To investigate whether CAFP and EF are conducive to remanufacturing, we first construct the benchmark model (including no capital constraint and a capital constraint without financing), and then construct the CF model (the scenario of the CAPF strategy) and EF model (the scenario of the EF strategy).

4.1. Benchmark model without financing

In this benchmark, remanufacturers use only their own funds to implement the production activities. The remanufacturer's expected profit is

$$\pi_m = (p_n - c_n)q_n + (p_r - c_r)q_r - p_c(1 + t)(E - L) \tag{4.1}$$

$$\text{s.t. } c_n q_n + c_r q_r \leq B \tag{4.2}$$

In Equation (4.1), the first term represents the revenue from new products (price minus unit cost, times quantity). The second term denotes the revenue from remanufactured products. The third term indicates the costs of (or revenue from) carbon trading. Specifically, if $E > L$, the remanufacturer has to spend the cost of $p_c(1 + t)(E - L)$ to purchase carbon assets; otherwise, it will gain the revenue of $p_c(1 + t)(L - E)$ from the cap-and-trade mechanism. Equation (4.2) ensures that total production cost does not exceed the available internal funds. When the constraint is binding ($c_n q_n + c_r q_r = B$), the firm is capital-constrained without financing (Model S). When it does not bind, the firm is well- funded (Model N). We can then obtain Lemma 1 and Lemma 2 (all proofs are given in the Appendix).

Lemma 1. *When the remanufacturer is well funded, the optimal production quantity of new and remanufactured products is*

$$q_n^N = \frac{\gamma_1 - \gamma_2}{2(1 - \delta)}, \quad q_r^N = \frac{\gamma_2 - \delta\gamma_1}{2\delta(1 - \delta)}.$$

Lemma 2. *When the remanufacturer has a capital constraint without financing, the optimal production quantity of new and remanufactured products is*

$$q_n^s = \frac{(\gamma_1 - \gamma_2) - \lambda(c_n - c_r)}{2(1 - \delta)}, \quad q_r^s = \frac{(\gamma_2 - \delta\gamma_1) + \lambda(c_n\delta - c_r)}{2\delta(1 - \delta)}.$$

Combined with Lemma 2, we can obtain the relationship of product yield, environmental impact, and initial capital shown in Proposition 1.

Proposition 1. *In Model S*

$$\frac{\partial q_n^s}{\partial B} > 0, \quad \frac{\partial p_n^s}{\partial B} < 0, \quad \frac{\partial q_r^s}{\partial B} < 0, \quad \frac{\partial p_r^s}{\partial B} < 0, \quad \frac{\partial E^s}{\partial B} > 0.$$

Proposition 1 indicates that in the capital-constrained scenario, the remanufacturer will adjust the output and price of new/remanufactured products according to the amount of initial capital to maximize profits. Specifically, because it may be more profitable to produce a new product than a remanufactured product, the remanufacturer will lower the price of both new and remanufactured products as the initial capital increases, increase the output of new products, and decrease the production of remanufactured products, with a corresponding increase in environmental impact. Therefore, remanufacturers can apply for CAPF loans or EF loans to solve the capital shortage problem and maximize profits.

4.2. The CAPF strategy (Model CF)

An emission-dependent remanufacturer can apply for CAPF loans to solve the problem of a lack of funds in the low-carbon economy. Since remanufacturers pay the CAPF loan interest, they cannot benefit from the CAPF loan if the return on the CAPF loan is less than the interest rate. Therefore, we need define the conditions for remanufacturers to apply for CAPF loans, which is presented in Proposition 2.

Proposition 2. *Only when the remanufacturers' initial capital complies with $B < \overline{B}$*

$$\overline{B} = \frac{(\gamma_1 - \gamma_2)\delta c_n + (\gamma_2 - \delta\gamma_1)c_r - r[\delta c_n(c_n - 2c_r) + c_r^2]}{2\delta(1 - \delta)},$$

they can profit from CAPF loans, but not otherwise.

Proposition 2 shows that it is not always profitable for remanufacturers to apply for the CAPF loans. Therefore, for capital-constrained remanufacturers, although CAPF provides a new channel to solve the problem of a lack of funds, remanufacturers still need to decide whether to apply for CAPF loans depending on their initial funds. They can benefit from CAPF only if their funds meet the condition $B < \bar{B}$.

For remanufacturers with a capital constraint, the order of events in Model CF is as follows: First, when the remanufacturer apply for CAPF from the banks, the banks will review the materials of the

remanufacturers. Second, if the application materials of the remanufacturers are qualified, the banks will sign the CAPF contract with the remanufacturer and decide on the pledge rate of the CAPF loan. After receiving the CAPF loans from banks, the remanufacturer will produce and sell products to customers. Finally, the remanufacturers will repay the principal and interest, and then redeem the pledged carbon asset. The detailed process is shown in Figure 3.
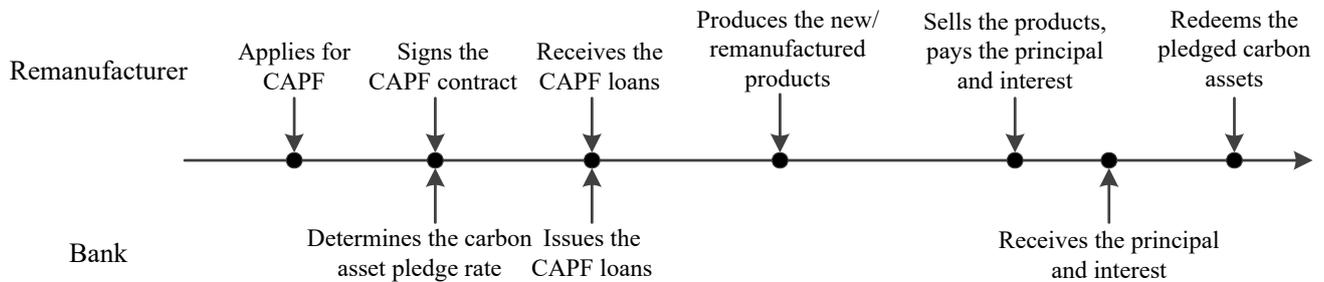

Figure 3. The operation process of CAPF.

In Model CF, the remanufacturer applies for a CAPF loan to supplement its internal funds. The loan amount is $p_e \theta L^{CF}$. The total available budget becomes $B + p_e \theta L^{CF}$, relaxing the capital constraint. However, the firm must repay the loan with interest at the end of the period, reducing net profit. The profit function becomes

$$\pi_m^{CF} = (p_n - c_n)q_n + (p_r - c_r)q_r - p_e(1 + t)(E^{CF} - L^{CF}) \quad -p_e \theta L^{CF} e^{rT} \qquad (4.3)$$

$$\pi_b^{CF} = p_e \theta L^{CF}(e^{rT} - 1) \qquad (4.4)$$

The new return $p_e \theta L^{CF}$ is the repayment amount (principal plus interest). This introduces a trade-off: The loan provides capital to increase production (especially of more profitable products), but the repayment reduces the final profit. Moreover, because L^{CF} depends on emissions, there is an indirect effect: Producing more increases emissions, which increases carbon assets and thus the loan amount, but also increases the carbon trading cost if emissions exceed allowances.

Lemma 3. *In Model CF, the optimal production quantity of new and remanufactured products is*

$$q_n^{CF} = \frac{(\gamma_1 - \gamma_2)(\xi_1 - \beta(\delta - \beta)) - \beta(1 - \beta)(\gamma_2 - \delta\gamma_1)}{4(1 - \delta)\xi_1},$$

$$q_r^{CF} = \frac{(\gamma_2 - \delta\gamma_1)[\delta(1 - \beta) + \xi_1] + \delta(\delta - \beta)(\gamma_1 - \gamma_2)}{4\delta(1 - \delta)\xi_1},$$

and the optimal pledged rate is

$$\theta^{CF} = \frac{(\gamma_1 - \gamma_2)\delta + \beta(\gamma_2 - \delta\gamma_1)}{2e^{rT}p_e \epsilon e_n \xi_1}$$

Corollary 1. *The production decisions of remanufacturers are not affected by the interest rate of the CAPF loan.*

Corollary 1 show that in the CF model, the interest rate of the CAPF loan has no correlation with the remanufacturers' production decision, which means that the remanufacturer is under pressure to repay the principal and interest. It will only formulate the optimal output according to its own capacity and market demand, which are not affected by the pressure of the CAPF loan, which is also consistent with reality.

Proposition 3.

$$\frac{\partial \theta}{\partial p_e} < 0, \quad \frac{\partial \theta}{\partial \epsilon} < 0, \quad \frac{\partial \theta}{\partial r} < 0, \quad \frac{\partial \theta}{\partial c_n} < 0, \quad \frac{\partial \theta}{\partial c_r} > 0.$$

Proposition 3 reveals that the bank will determine θ according to the application materials of the remanufacturer, the carbon price, etc. Specifically, an increase in ϵ, p_e, r, and c_n will decrease θ, and an increase in c_r will increase θ. This is because an increase in ϵ and p_e will increase the risk of CAPF, and banks thus reduce θ. Meanwhile, an increase in r will increase the pressure of remanufacturers; to attract more remanufacturers to carry out CAPF, banks will correspondingly reduce θ. In addition, the main purpose of CAPF is to encourage firms to produce more low-carbon products (remanufactured products) and fewer high-carbon products (new products). Therefore, banks will adjust θ according to c_n, c_r.

Proposition 4. *If r is given,*

$$\frac{\partial q_n^{CF}}{\partial \theta} < 0, \quad \frac{\partial q_r^{CF}}{\partial \theta} > 0;$$

if θ is given,

$$\frac{\partial q_n^{CF}}{\partial r} < 0, \quad \frac{\partial q_r^{CF}}{\partial r} > 0.$$

Proposition 4 reveals that when remanufacturers apply for the CAPF loans, if banks set r as a certain value, the increase in θ will increase the yield of remanufactured products and decrease the yield of new products. If banks set θ as a certain value, the increase in r will increase the yield of remanufactured products and decrease the yield of new products. This indicates that if r (or θ) is required to remain unchanged, banks can adjust θ (or r) to promote the development of remanufacturing.

4.3. EF strategy (Model EF)

For capital-constrained remanufacturers, the orders of events for applying for the EF loan is as follows: First, when remanufacturers apply for EF from investors, investors will review the application materials of the remanufacturer. Second, investors will sign the EF contract according to the remanufacturers' materials and determine the percentage of dividends α. After receiving the EF loans from investors, remanufacturers will produce and sell products to the customers. Finally, the remanufacturers will pay dividends to the investors according to the agreed percentage. The detailed process is shown in Figure 4.
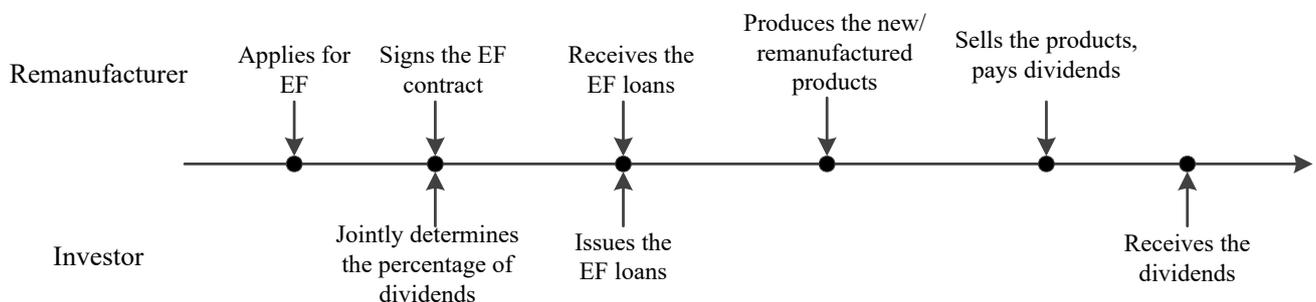

Figure 4. The order of events in the EF Model.

In Model EF, the remanufacturer raises external funds by selling an equity stake. Investors provide the capital $B^* = B^N - B$ (the shortfall relative to the well-funded scenario) in exchange for a fraction α

of the remanufacturer's profits. The profit after dividend payment is:

$$\pi_m^{EF} = (1 - \alpha)[(p_n - c_n)q_n + (p_r - c_r)q_r - p_e(1 + t)(E^{EF} - L^{EF}) + B^*] - B \tag{4.5}$$

$$\pi_e^{EF} = \alpha[(p_n - c_n)q_n + (p_r - c_r)q_r - p_e(1 + t)(E^{EF} - L^{EF}) + B^*] - B^* \tag{4.6}$$

The investor provides B^* upfront and receives a share α of the terminal profit (which includes the initial capital). Note that the total profit before dividends is the same as in Model N (the well-funded case) because the firm has sufficient capital. Therefore, the optimal production quantities in Model EF are identical to those in Model N (Lemma 4). This is a key insight: EF, by fully relieving the capital constraint, allows the firm to operate at the first-best production levels, but at the cost of diluting profits.

Lemma 4. *In Model EF, the optimal production quantity of new and remanufactured products is*

$$q_n^{EF} = q_n^N = \frac{\gamma_1 - \gamma_2}{2(1 - \delta)}, q_r^{EF} = q_r^N = \frac{\gamma_2 - \delta\gamma_1}{2\delta(1 - \delta)}.$$

Lemma 4 reveals that the remanufacturer's optimal production strategy under Model EF is the same as under Model N. This is because in Model EF, the remanufacturer does not have to repay back capital and interest does not have to bear the risk of debt but only pays dividends to the investor according to a certain proportion of the sales profit. Therefore, in Model EF, the remanufacturer has access to sufficient capital and makes the same optimal production decision as in Model N.

Corollary 2. *Only when the EF dividend ratio meets the condition $\alpha_1 < \alpha < \alpha_2$ with*

$$\alpha_1 = \frac{4\delta(1 - \delta)B^*}{\gamma_1(\gamma_1 - \gamma_2) + \gamma_2(\gamma_2 - \delta\gamma_1) + 2\delta(1 - \delta)B^*}, \qquad \alpha_2 = 1 - \frac{4\delta(1 - \delta)B}{\gamma_1(\gamma_1 - \gamma_2) + \gamma_2(\gamma_2 - \delta\gamma_1) + 2\delta(1 - \delta)B^*},$$

the remanufacturer and the investor both accept the EF strategy.

Corollary 2 reveals that the boundary condition for the EF strategy depends on the dividend ratio; the remanufacturer and the investor accept the EF strategy only if the dividend ratio satisfies $\alpha_1 < \alpha < \alpha_2$. This is because, in the EF model, remanufacturers have to pay dividends to investors, and the profits of both parties are affected by the dividend payout ratio.

Proposition 5.

$$\frac{\partial q_n^J}{\partial p_e} < 0, \ \frac{\partial q_r^J}{\partial p_e} < 0, \ \frac{\partial q_n^J}{\partial t} < 0, \ \frac{\partial q_r^J}{\partial t} < 0, \ \frac{\partial q_n^J}{\partial \epsilon} > 0, \ \frac{\partial q_r^J}{\partial \epsilon} > 0, \quad (J = CF, EF).$$

Proposition 5 reveals that when making optimal production decisions, remanufacturers need to consider carbon prices and carbon asset holdings, i.e., the increase in p_e; the emission price volatility t will decrease the output of products (including new/remanufactured products); and the increase in ϵ will increase the output of products (including new/remanufactured products). This is because an increase in t and p_e will increase the pressure to repay the EF loan, and remanufacturers will have to reduce the output of products. In addition, an increase in ϵ will increase the amount of the EF loan, reduce the financial pressure, and encourage remanufacturers to expand the production of products.

Proposition 6.

$$q_n^{EF} > q_n^{CF}, \qquad q_r^{EF} < q_r^{CF}, \qquad E^{EF} > E^{CF}.$$

Proposition 6 reveals that compared with the case of CAPF, the adoption of EF can increase the yield of new products and the total carbon emissions, and decrease the yield of remanufactured products. This means that the CAPF is more beneficial than the EF in terms of emissions reduction and remanufacturing.

5. Results

In this section, we use numerical experiments to analyze the influence of CAPF and EF on the optimal equilibrium solution of remanufacturers. For remanufacturers with capital constraints, how to evaluate the impact of different financing modes is a pressing issue. Therefore, we propose the concept of the financing contribution rate C_j^i and develop a model to measure the contribution rates of CAPF and EF. The formula is as follows:

$$C_j^i = \frac{j^i - j^s}{j^N - j^s}, \qquad (i = CF, EF, \ j = q_n, q_r, E, CS, \pi_m, \pi_b, \pi_e).$$

This provides a way to assess the effectiveness of different financing strategies and enhance the scientific nature of financing decisions for remanufacturers. Through surveys of Caterpillar and Sany Group, we found that remanufactured products generate unit costs and unit carbon emissions less than half those of their new counterparts. Referring to Ding et al. [18] and the trend extrapolation method, etc., we set the parameters as $c_n = 0.5$, $c_r = 0.2$, $e_n = 0.5$, $p_e = 0.4$, $t = 0$, $\beta = 0.3$, and $\epsilon = 0.95$. Considering that the remanufacturing industry is in its development stage and is affected by factors such as talent shortage and an imperfect quality control system for remanufacturing, the consumption preference for remanufactured products of consumers is set as $\delta = 0.6$. In addition, referring to the case of the Industrial Bank providing CAPF loans to Hubei Yihua Group, we set the pledge period for the enterprise's CAPF loan as three years, and the interest rate for the CAPF loan as 0.05; that is, $T = 3$, $r = 0.05$. Then we set the initial capital as $B = 0.01$, which meets the boundary condition of CAPF.

5.1. Sensitivity analysis

To further verify the validity of the parameter assignment and enhance the robustness of our research conclusions, we conducted a sensitivity analysis of the key parameters. Table 4 shows the changes in the optimal production quantities for models CF and EF when analyzing the parameters p_e, ϵ, δ, t, β, c_n, and c_r. In Table 4, as the coefficient of carbon assets ϵ increases, remanufacturers obtain more tradable allowances under the carbon market, causing the output of both new and remanufactured products to increase. Moreover, a higher carbon trading price and emission price volatility lead to a reduction in the production of high-cost new products and an expansion in the output of low-cost remanufactured products. A higher β (less reduction in emissions from remanufacturing) reduces the advantage of remanufactured products, and a higher δ (greater consumer acceptance of remanufactured products) increases demand for both products, raising outputs. This is consistent with the actual situation and the results obtained from Proposition 3 and Proposition 5. In addition, a higher c_n reduces new product output while boosting remanufactured output in both financing models, consistent with the substitution effect between product types. Conversely, an increase in c_r suppresses remanufactured output, confirming that higher remanufacturing costs hinder the development of remanufacturing even under CAPF or EF. These results remain qualitatively consistent with Propositions 3 and 6, thereby reinforcing the robustness of our conclusions.

Table 4. Effect of $p_e, \epsilon, \delta, t, \beta, c_n,$ and c_r on the optimal production quantities in Models CF and EF.

p_e	ϵ	δ	t	β	c_n	c_r	q_n^{CF}	q_r^{CF}	q_n^{EF}	q_r^{EF}
0.2	0.95	0.6	0	0.3	0.5	0.2	0.0035	0.2951	0.1206	0.2115
0.3	0.95	0.6	0	0.3	0.5	0.2	0.0024	0.2959	0.1184	0.2130
0.4	0.95	0.6	0	0.3	0.5	0.2	0.0013	0.2967	0.1163	0.2146
0.4	0.97	0.6	0	0.3	0.5	0.2	0.0031	0.2954	0.1198	0.2121
0.4	0.99	0.6	0	0.3	0.5	0.2	0.0048	0.2942	0.1233	0.2096
0.4	0.95	0.7	0	0.3	0.5	0.2	0.0030	0.3294	0.1274	0.2375
0.4	0.95	0.8	0	0.3	0.5	0.2	0.0047	0.3621	0.1384	0.2603
0.4	0.95	0.6	0.1	0.3	0.5	0.2	0.0007	0.2970	0.1152	0.2154
0.4	0.95	0.6	0.2	0.3	0.5	0.2	0.0001	0.2974	0.1141	0.2160
0.4	0.95	0.6	0	0.2	0.5	0.2	0.0029	0.2989	0.1203	0.2121
0.4	0.95	0.6	0	0.1	0.5	0.2	0.0045	0.3012	0.1245	0.2098
0.4	0.95	0.6	0	0.3	0.48	0.2	0.0021	0.2961	0.1190	0.2126
0.4	0.95	0.6	0	0.3	0.52	0.2	0.0005	0.2972	0.1135	0.2165
0.4	0.95	0.6	0	0.3	0.5	0.19	0.0019	0.2970	0.1171	0.2151
0.4	0.95	0.6	0	0.3	0.5	0.18	0.0025	0.2973	0.1178	0.2156

5.2. Production properties

To compare the influence of CAPF and EF on the remanufacturer's production decision, Figure 5 shows the effect of the parameter δ on production volumes. Compared with the capital constrained without financing, the adoption of CAPF and EF can increase the volume of new products. This is because remanufacturers repay the interest on the CAPF loan in the Model CF or pay the dividends to investors in Model EF, which increase the financial pressure on the remanufacturer, and the remanufacturer will expand the production of new products with higher unit profits than in the scenario without financing. In addition, the volume of remanufactured products in Model EF is higher than in Model CF, suggesting that CAPF is beneficial for promoting remanufacturing, which is also consistent with the purpose of CAPF.
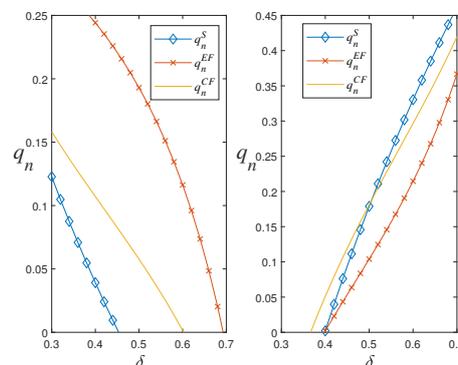

Figure 5. Effects of δ on the yield.

Figure 6 shows the effect of δ on the rate of financing contribution to output in Models CF and EF. Compared with the EF, the CAPF contribution rate to the yield of remanufactured products is higher, and the CAPF contribution rate to the yield of new products is lower. Meanwhile, an increase in δ will also increase the contribution rate of CAPF to new/remanufactured products, but have no influence on the contribution rate of EF new products and remanufactured products. This is because the yield of remanufactured products in Model EF is the same as in Model S, and δ has no effect on the contribution rate of EF to output.
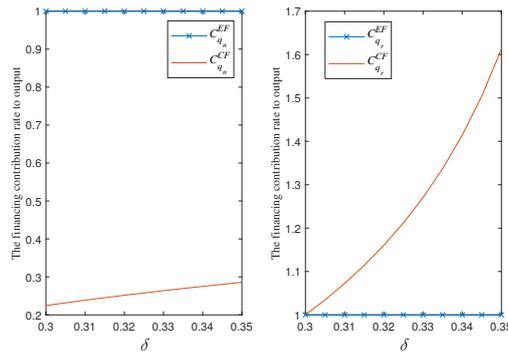
Figure 6. Effects of δ on the rate of financing contribution to yield.

5.3. *The carbon asset pledge rate*

Figure 7 illustrates the effect of δ, t, β, and r on the optimal carbon asset pledge rate θ. It implies that banks need to consider many factors such as the product market and carbon trading market when setting θ. Specifically, θ will decrease as the related parameters δ, t, and r increase and will increase as the parameter β increases. The reason can be explained as follows: β and t will increase the fluctuation of CAPF business, and banks will lower θ to avoid business risks. The increase in r will increase the amount of CAPF loans, and banks will also reduce θ for the same reason. In addition, an increase in β will reduce the low-carbon advantage of remanufactured products, and banks will increase the amount of CAPF loans by increasing θ, encouraging remanufacturers to increase their investment in emission reduction to increase the low carbon benefit of their products.
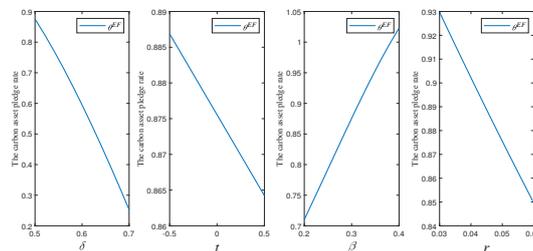
Figure 7. Effects of δ, t, β, and r on the carbon asset pledge rate.

5.4. *Environmental performances*

Figure 8 illustrates the effect of δ, t, and β on the environmental impact. It means that no matter how the parameters δ, t, and β change, adopting CAPF and EF can increase the environmental impact

compared with the case of capital constraint without financing, and the environmental impact in Model EF is always higher than that in Model CF. This is because remanufacturers will produce new products with higher profit per unit in Model EF and Model CF, and the environmental impact will increase accordingly due to the higher carbon emissions of new products. Figure 9 shows the influence of δ, t, and β on the contribution rate of CAPF/EF to environmental impact. Compared with EF, the adoption of CAPF has a lower contribution rate to the environmental impact, and whether the contribution rate of CAPF to the environmental impact increases or decreases is also affected by consumer preferences and emission price volatility.
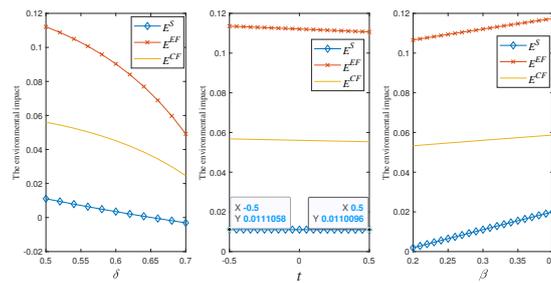
Figure 8. Effects of δ, t, and β on environmental impact.
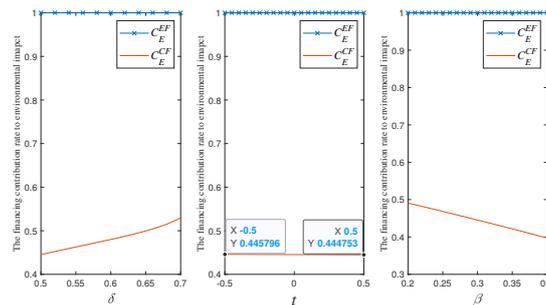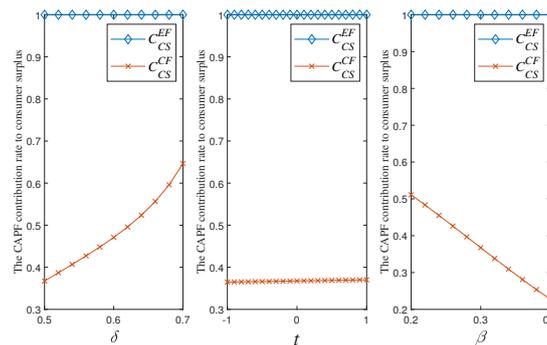

Figure 9. Effects of δ, t, and β on the contribution rate of CAPF to environmental impact.

5.5. Consumer surplus performances

According to He et al. [48], we know that the consumer surplus is the sum of surplus for all products purchased by consumers, and the formula of consumer surplus is:

$$CS = \int_{\frac{p_n - p_r}{1-\delta}}^{1} (\theta - p_n)\, d\theta + \int_{\frac{p_r}{\delta}}^{\frac{p_n - p_r}{1-\delta}} (\delta\theta - p_r)\, d\theta = \frac{(q_n)^2 + \delta(q_r)^2 + 2\delta q_n q_r}{2}. \tag{5.1}$$

Figure 10 illustrates the effect of δ, t, and β on the consumer surplus. It implies that no matter how the parameters δ, t, and β change, adopting CAPF and EF can increase the consumer surplus compared with the scenario of capital constraint without financing, and the consumer surplus in Model EF is always higher than that in Model CF. In addition, as δ increases, the consumer surplus will increase, and as t and β increase, the consumer surplus will decrease. This is because the increase in δ indicates the maturity of the remanufacturing market, in which remanufacturers will produce more products, and the consumer surplus will increase accordingly. The fluctuation of CAPF business will increase as

t and β increase, the amount of CAPF loans will decrease, and remanufacturers will produce fewer products, so the consumer surplus will decrease accordingly. Figure 11 shows the effect of δ, t, and β on the contribution rate of CAPF and EF to consumer surplus. Compared with EF, the contribution rate to consumer surplus under CAPF is always lower, and whether the contribution rate to consumer surplus under CAPF increases or decreases is also affected by consumer preferences and emission price volatility.
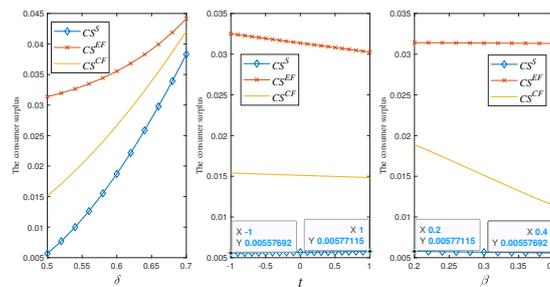
Figure 10. Effects of δ, t, and β on consumer surplus.

Figure 11. Effects of δ, t, and β on the CAPF/EF contribution rate to consumer surplus.

5.6. Economic performances

Table 5 shows the effect of δ, t, β, and α on the profits of remanufacturers and banks. As seen in Table 5, if the share of dividends between the remanufacturer and the investor is below a threshold range, the profit of remanufacturers in the EF model will be higher than the profit in the CF model, and vice versa. Therefore, the remanufacturer should choose between EF or CAPF depending on the value of the dividend ratio. In addition, whether remanufacturers adopt CAPF/EF, or remain without financing, as consumer preference δ increases, the profit of remanufacturers will increase, but the profit of banks will decrease; with an increase in t and β, the profit of remanufacturers will decrease, but the profit of banks will increase. Therefore, the government can strengthen the popularization of green concepts among consumers and provide subsidies for companies to promote remanufacturing. In addition, when $\alpha = 0.049$, the profits of the remanufacturer under the CAPF and EF models are equal. Therefore, for remanufacturers with capital constraints, if the dividend ratio exceeds a certain threshold, choosing CAPF is more advantageous; otherwise, choosing EF is more advantageous.

Table 5. Economics performance with different key parameters.

Parameters	π_m^S	π_m^{EF}	π_m^{CF}	π_b
$\delta = 0.4,\ \beta = 0.3,\ \alpha = 0.5,\ t = 0$	0.018	0.01	0.0154	0.0042
$\delta = 0.5,\ \beta = 0.3,\ \alpha = 0.5,\ t = 0$	0.0263	0.0114	0.0291	0.0032
$\delta = 0.6,\ \beta = 0.3,\ \alpha = 0.5,\ t = 0$	0.0486	0.0155	0.0527	0.0017
$\delta = 0.6,\ \beta = 0.4,\ \alpha = 0.5,\ t = 0$	0.0482	0.0154	0.0436	0.0026
$\delta = 0.6,\ \beta = 0.5,\ \alpha = 0.5,\ t = 0$	0.0479	0.0153	0.0333	0.0035
$\delta = 0.6,\ \beta = 0.3,\ \alpha = 0,\ t = 0$	0.0486	0.0611	0.0527	0.0017
$\delta = 0.6,\ \beta = 0.3,\ \alpha = 0.1,\ t = 0$	0.0486	0.044	0.0527	0.0017
$\delta = 0.6,\ \beta = 0.3,\ \alpha = 0.2,\ t = 0$	0.0486	0.0369	0.0527	0.0017
$\delta = 0.6,\ \beta = 0.3,\ \alpha = 0.5,\ t = -2$	0.0487	0.0174	0.0535	0.002
$\delta = 0.6,\ \beta = 0.3,\ \alpha = 0.5,\ t = 0$	0.0486	0.0155	0.0527	0.0017
$\delta = 0.6,\ \beta = 0.3,\ \alpha = 0.5,\ t = 2$	0.0484	0.0138	0.0519	0.0015
$\delta = 0.6,\ \beta = 0.3,\ \alpha = 0.049,\ t = 0$	0.0017	0.0527	0.0527	0.0831

Figure 12 shows the influence of δ, t, and β on the contribution rate of CAPF/EF to the profit of remanufacturers. When the dividend ratio is a certain value ($\alpha = 0.5$) under EF, the contribution rate to the profit increases or decreases, but this is also affected by consumer preferences, emission price volatility, and unit emissions of remanufactured products.
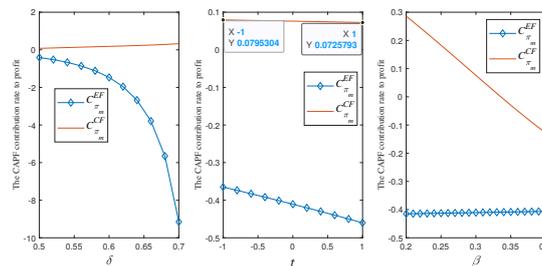
Figure 12. Effects of δ, t, and β on the contribution rate of financing to remanufacturers' profit.

6. Conclusions

Motivated by the practice of CAPF, we study the role of CAPF and EF in the operational decision of a monopolistic remanufacturer and develop the optimal production decision model under CAPF and EF. We define the boundary conditions of CAPF and EF adopted by remanufacturers, and compare the impact of emission price volatility and other key parameters on the equilibrium results under CAPF and EF. The main conclusions are presented below.

(1) When the emission-dependent remanufacturer has inadequate funding, whether to adopt EF or CAPF is determined by the dividend ratio or the initial capital. The condition for the remanufacturer to profit from CAPF loans is $B < \overline{B}$; the condition for both parties to accept EF is $\alpha_1 < \alpha < \alpha_2$.

(2) Compared with the scenario of capital constraint without financing, the adoption of CAPF or EF can always increase the yield of new products, the environmental impact, and the consumer surplus. In Model CF, the yield of remanufactured products is higher than that in Model EF, but the environmental impact and consumer surplus are lower than that in Model EF. In addition, the rate of contribution to the

yield of remanufactured products under CAPF is always higher than that under EF, while the rate of contribution to environmental impact and consumer surplus under EF is always higher than that under CAPF.

(3) For the capital-constrained and emissions-dependent remanufacturer, regardless of whether CAPF or EF is adopted, an increase in emission price volatility and an decrease in the emission advantages of remanufactured products will reduce profits. Meanwhile, whether the profit and the contribution of financing to profit under EF is higher than that under CAPF is determined by the dividend ratio threshold. Therefore, remanufacturers can choose the most favorable financing strategy depending on their own initial capital and the dividend ratio formulated with investors.

This work offers the following management insights.

For capital-constrained remanufacturers, the optimal financing choice depends on the firm's characteristics. Large, emission-intensive firms with substantial carbon assets should prioritize CAPF, as it yields higher profit than EF and reduces carbon emissions, and these firms can negotiate higher pledge rates to maximize loan amounts. Small and medium enterprises (SMEs) with limited carbon assets face higher CAPF barriers; they should first build carbon portfolios through gradual emission reductions, and consider EF only when dividend ratios are low. High-carbon remanufacturers benefit from CAPF's alignment with emission reduction, as the loan amounts scale with emissions, incentivizing cleaner production. Low-carbon firms have fewer assets to pledge and may find EF more accessible. For all remanufacturers, the choice between CAPF and EF hinges on the dividend ratio and their carbon asset endowment.

For policymakers, the government should design carbon allocation rules that enhance CAPF's accessibility, such that a higher coefficient of carbon assets increases loan availability and incentivizes remanufacturing, and the carbon price stabilization mechanisms are also critical. To support SMEs' participation, governments should offer credit guarantees for CAPF and develop aggregation mechanisms allowing SMEs to pool allowances. Incorporating CAPF into the green finance classification system and standardizing the pledge procedures will reduce transaction costs and attract institutional investors, thereby enhancing the emission reduction advantages of CAPF, while maintaining the profitability of enterprises and accelerating the low-carbon transformation of energy-intensive industries.

This paper introduces the new financing pattern (CAPF) into remanufacturing management, and examines the effects of CAPF and EF on the operations of a monopolistic remanufacturer. Nevertheless, our scope is limited: We focus on a deterministic demand setting and disregard broader dimensions such as no economies of scale, quality uncertainty, regulatory risk, and risk aversion; uncertain demand would be more realistic. Moreover, we examine only CAPF and EF, whereas additional financing channels exist in practice; extending the model to incorporate these alternatives constitutes a promising avenue for future research.

Author contributions

Shuaishuai Fu: Conceptualization, methodology, writing original draft. Dandan Wang: Writing – review and editing, Supervision. Chengya Lin: Validation. Zhuoer Li: Visualization.

Conflict of interest

There are no relevant financial or non financial competing interests to declare.

Data availability

Data sharing is not applicable to this article, as no data were created or analyzed in this study.

Use of Generative-AI tools declaration

The authors declare that no generative AI tools were used in the preparation of this manuscript. All content is the original work of the authors.

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