Research on Remanufacturing Reverse Supply Chain Optimization Strategies Driven by Enhanced Carbon Reduction Capability

Zuzhen Zhang

Tianjin University of Technology and Education, School of Economics and Management, Tianjin 300222, China

Abstract

The reverse supply chain is a key driver of the circular economy, and its low-carbon operation plays a vital role in achieving the "Dual Carbon" goals. To address this issue, this study takes the remanufacturing rate (q_r) as a core variable, constructs a two-tier remanufacturing reverse supply chain system dynamics model. The model analyzes the impact mechanism of q_r on the carbon emissions of supply chain members. By enhancing carbon emission reduction capability, it investigates the phased characteristics of carbon reduction investment strategies to optimize the low-carbon operation of the reverse supply chain. Built on the Vensim platform, the model with carbon emission features from processes including treatment, disassembly, retreatment, and remanufacturing. Simulation results reveal that collector' carbon emissions decline as q_r grows, while remanufacturer' emissions peak at moderate q_r levels. When carbon reduction investments are introduced, the optimal strategies of the collector and the remanufacturer present phased characteristics with distinct critical thresholds. The study offers theoretical and quantitative support for corporate carbon reduction decisions and differentiated policy-making in reverse supply chains.

Keywords

Reverse Supply Chain; Carbon Emission; System Dynamics; Remanufacturing Rate; Carbon Emission Reductionintroduction.

1. Introduction

As global climate challenges intensify, governments are implementing stringent carbon reduction policies, such as emissions trading systems, to drive corporate green transformation. In this context, reverse supply chains are vital for achieving China's "Dual Carbon" goals, yet collectors and remanufacturers face the dual challenges of carbon emission constraints and economic viability. Although investments in carbon reduction technologies can mitigate emissions, they incur additional costs[1]. Therefore, formulating optimal carbon reduction strategies in this complex environment is an urgent challenge.

The remanufacturing rate serves as a critical mediating variable that determines resource consumption intensity and profitability. However, existing studies have not fully explored how carbon emissions dynamically affect collectors' collection rates and remanufacturers' satisfaction rates when considering this variable. Specifically, high emissions increase carbon compliance costs, which subsequently reduce collection capacity and lower market demand for remanufactured products. Consequently, both parties have clear incentives to invest in carbon reduction.

Building on[2], this study develops a system dynamics (SD) model for a two-tier reverse supply chain to analyze: (1) The impact mechanism of the remanufacturing rate on carbon emissions: Quantifying how varying remanufacturing rates influence the carbon reduction potential of the supply chain.(2) Decision-making on carbon reduction investments: Determining appropriate investment levels to balance environmental benefits with economic returns under varying remanufacturing rates.

The main innovations include: (1) innovatively constructing an SD model with a market feedback mechanism that incorporates the remanufacturing rate into carbon reduction decisions; and (2) integrating CCUS technology to identify differentiated investment thresholds and optimal strategies for supply chain members. This research enriches reverse supply chain theory and provides practical, phased investment guidelines for enterprises, as well as a scientific basis for government incentive policy design.

2. Literature Review

Research on the remanufacturing rate mainly explores its determinants in three dimensions: quality uncertainty, collection mode selection, and policy incentives. Regarding the impact of quality uncertainty on this rate, Pazouki et al[3]. constructed a manufacturing/remanufacturing system inventory model to reveal the intrinsic link between forward and reverse product quality; their findings indicate that super-standard quality production strategies enhance remanufacturing feasibility and system economic-environmental benefits, providing theoretical support for rate improvement via quality control. In terms of collection mode selection, Long et al[4]. used a Stackelberg game model and found that remanufacturing rate acts as both a threshold and a moderating factor in collection mode decisions: when the rate is elevated, enterprises tend to adopt independent remanufacturing and competitive strategies; when the rate is reduced, they prefer cooperation or reselling products to manufacturers to balance economic and operational risks. Although the aforementioned studies focused solely on remanufacturing rate without incorporating carbon emission factors, with the advancement of global carbon neutrality goals, integrating carbon-related considerations into remanufacturing research has emerged as a frontier trend.

Carbon reduction is a critical objective for the sustainable development of reverse supply chains. Existing study on carbon emissions primarily focuses on three aspects: transportation optimization, remanufacturing strategy selection, and government policy regulation. Ullah[5] found that transportation distance significantly affects both remanufacturing rate and carbon emissions in reverse supply chains. Long-distance transportation reduces the economic viability of remanufacturing and may increase net emissions . Regarding the carbon reduction effects of remanufacturing strategies. Zhou et al[6]. further emphasized that carbon trading prices influence firms' remanufacturing strategy choices, firms tend to adopt licensed remanufacturing when carbon prices are modest, whereas they prefer in-house remanufacturing when prices are elevated. Concerning the regulatory role of government policies, Zhang et al[7]. considered supply chain strategy choices under carbon quota and trading mechanisms, carbon reduction technology investment, and consumers' low-carbon preferences. They pointed out that timely government incentives can encourage firms to invest in emission reduction technologies and boost profits. These studies recognize the importance of carbon emissions in reverse supply chains. They also explore relevant emission reduction strategies. Yet they fail to fully analyze the long-term carbon emission behavioral dynamics among supply chain members.

With regard to the application of system dynamics (SD) in analyzing the long-term behavior of reverse supply chain members. Gu et al[8]. developed a system dynamics model to explore optimal decisions on remanufacturing rate and remanufacturing initiation period. They examined the long-term dynamics of a Manufacturing/Remanufacturing (R/M) integrated supply chain, while offering simulation-derived insights for joint decision-making among supply chain members. Vlachos et al[9]. developed a system dynamics based simulation model by incorporating both economic and environmental objectives of remanufacturing facilities. They assessed the effects of various capacity planning policies on long-term supply chain profitability, thus providing an experimental tool to support strategic decision-making. Similarly, Mutingi[10] utilized system dynamics to assess the impact of reverse logistics on the environmental, social, and economic performance of green supply chains. He emphasized that investments in green strategies should adopt a medium-to-long-term orientation. Golroudbary et al[11]. underscored the urgency of closed-loop supply chain management in addressing environmental challenges. Their system dynamics simulations revealed that incorporating collectors markedly improves customer satisfaction and the green image index, thus providing empirical evidence to inform the practical implementation of closed-loop supply chains. Luo et al[12]. focused on a supply chain consisting of a single manufacturer and a single retailer. They assessed the effects of carbon cap policies via an SD model, while accounting for whether supply chain members invest in carbon reduction technologies. They found that when the relationship between carbon trading prices and carbon caps is linear, neither supply chain nor manufacturer profits increase linearly with higher caps. This may diminish firms' incentive to cut emissions. Thus, they suggested integrating consumer low-carbon preferences to enhance policy effectiveness. However, while the aforementioned studies have systematically explored the long-term interactions between remanufacturing, collection strategies, and carbon policies, they have generally treated remanufacturing rate as an exogenously given or fixed parameter. They fail to reveal the long-term impact mechanism of its dynamic changes on supply chain carbon emissions, and this research gap has provided an important direction for future studies.

3. Model Construction

3.1 Problem Description

This study constructs a two-tier remanufacturing reverse supply chain system dynamics model that includes a collector and a remanufacturer. The collector collects used products from the market, and after inspection, sells the "remanufacturable products" to the remanufacturer. Within the remanufacturer, there are specialized departments for disassembly, part remanufacturing, and remanufactured assembly. Based on market demand forecasts for remanufactured products, the remanufacturer first estimates its remanufacturing capacity according to its operational scale and purchases parts for remanufacturing from the collector. These purchased parts are then disassembled to obtain actually usable parts, which are subsequently remanufactured, assembled, and finally sold to the market. These process forms a complete closed-loop encompassing new product sales, used product collection, and remanufacturing followed by market launch. As noted in[2], due to both technical and non-technical factors, inspection errors may occur, such that some "non-remanufacturable products" are inspected as remanufacturable products, while some "remanufacturable products" are inspected as non-remanufacturable products. Hence, the presence or absence of quotation marks in describing these categories conveys distinct meanings.

The model retains the assumption of inspection error rates from previous studies but does not emphasis on this aspect. Building on[2], it incorporates carbon emission considerations. Specifically, it accounts for carbon emissions from collector's treatment process and remanufacturer' s disassembly, retreatment, and remanufacturing processes. the data are prepared based on ISO 14067:2018 Greenhouse Gases - Carbon Footprint of Products - Requirements and Guidelines for Quantification.All carbon emissions are unified as CO_2 equivalent (CO_2e). It is proposed that carbon emissions from the treatment process influence the collector's collection rate, while emissions from disassembly, retreatment, and remanufacturing affect the remanufacturer's satisfaction rate in the demand market, as illustrated in Figure1.

However, when the collector and the remanufacturer consider carbon reduction technology investments to decrease the carbon emissions generated per unit of product during treatment, disassembly, retreatment, and remanufacturing, such investments inevitably incur additional costs for both parties. Nevertheless, carbon emissions directly influence collector's collection rate and the remanufacturer's satisfaction rate. Thus, adopting these technologies will in turn impact both overall carbon emissions and the profit levels of each party.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202607_12(7).0004

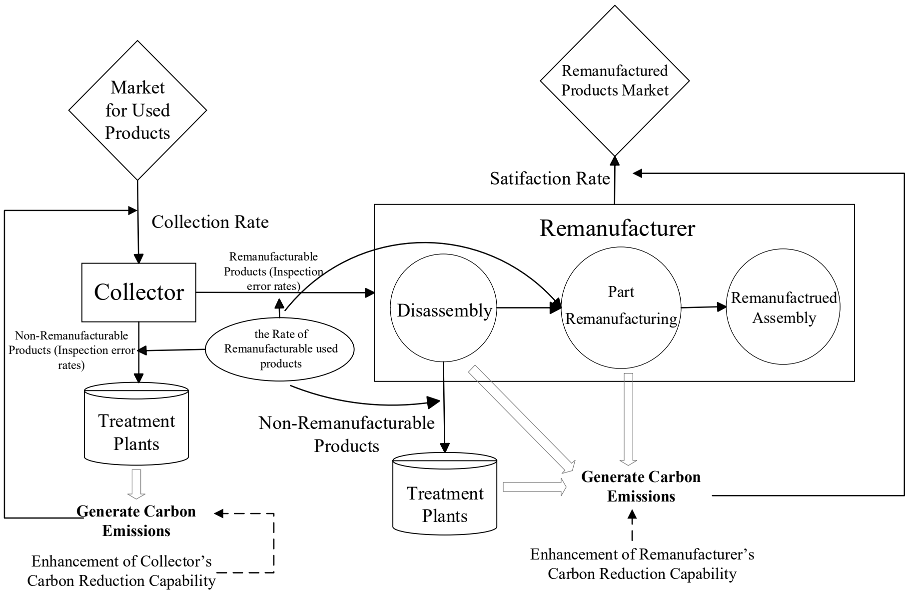

Figure 1. Remanufacturing reverse supply chain

3.2 Model Construction

Subsequently, the reverse supply chain system dynamics model for remanufacturing is constructed using the system dynamics software Vensim (The bold variables represent supplementary additions to the baseline model.). In Vensim, system dynamics models are represented by stock-and-flow diagrams and related equations, as illustrated in Figures 2.

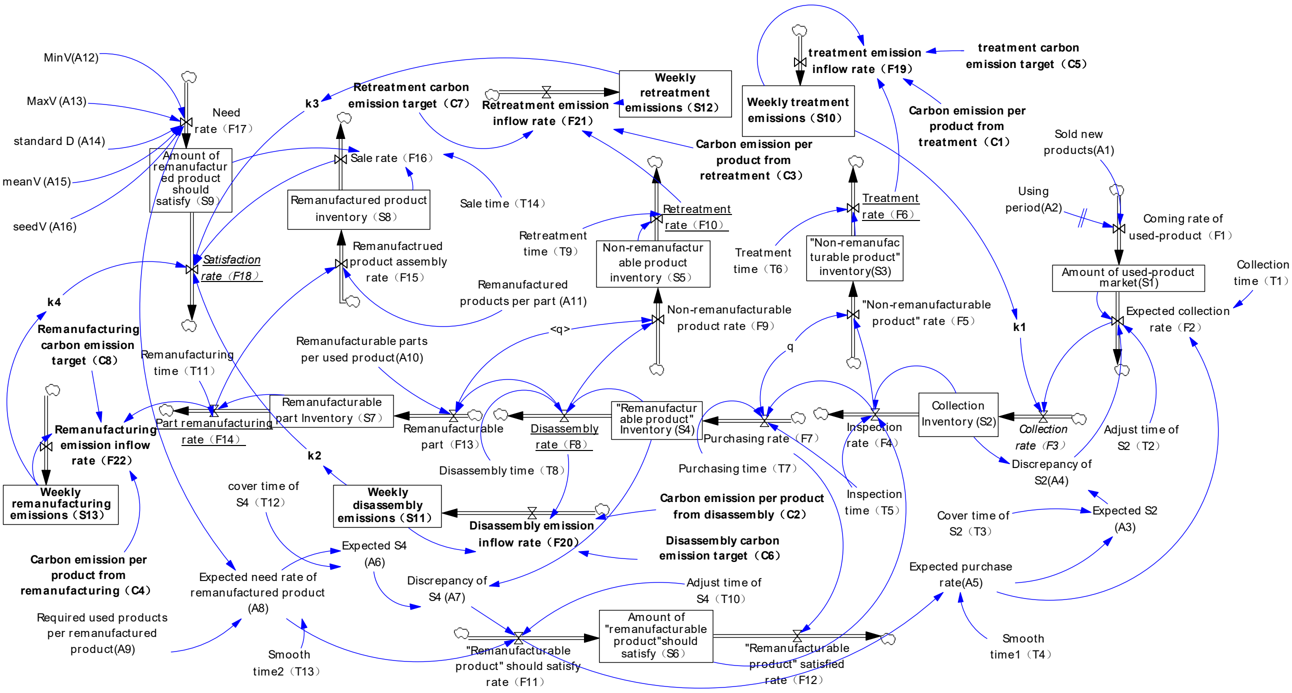

Figure 2. Stock-flow diagramThe model includes stocks, flows, and auxiliary variables, as presented in Tables 1.

Table 1. Stocks, auxiliary and flow variables

Stock	Unit	Auxiliary Variable	Unit
Amount of used-product market (S1))	piece	Expected S2 (A3)	piece
Collection Inventory (S2)	piece	Discrepancy of S2 (A4)	piece
"Non-remanufacturable product" inventory (S3)	piece	Expected purchase rate (A5)	piece/week
"Remanufacturable product" Inventory (S4)	piece	Expected S4 (A6)	piece
Non-remanufacturable product inventory (S5)	piece	Discrepancy of S4 (A7)	piece
Amount of "remanufacturable product"should satisfy(S6)	piece	Expected need rate of remanufactured product (A8)	piece/week
Remanufacturable part inventory(S7)	piece	Treatment coefficient(k1)	Dmnl
Remanufactured product inventory(S8)	piece	Disassembly coefficient(k2)	Dmnl
Amount of remanufactured product should satisfy(S9)	piece	Retreatment coefficient(k3)	Dmnl
Weekly treatment emissions(S10)	$kgCO_2e$	Remanufacturing coefficient(k4)	Dmnl
Weekly disassembly emissions(S11)	$kgCO_2e$		
Weekly retreatment emissions(S12)	$kgCO_2e$		
Weekly remanufacturing emissions(S13)	$kgCO_2e$		

Flow	Unit	Flow	Unit
Coming rate of used-product(F1)	piece/week	"Remanufacturable product" satisfied rate(F12)	piece/week
Expected collection rate(F2)	piece/week	Remanufacturable part(F13)	piece/week
Collection rate(F3)	piece/week	Part remanufacturing rate(F14)	piece/week
Inspection rate(F4)	piece/week	Remanufactrued product assembly rate(F15)	piece/week
"Non-remanufacturable product" rate(F5)	piece/week	Sale rate(F16)	piece/week
Treatment rate(F6)	piece/week	Need rate(F17)	piece/week
Purchasing rate(F7)	piece/week	Satisfaction rate(F18)	piece/week
Disassembly rate(F8)	piece/week	Treatment emission inflow rate(F19)	kgCO2/week
Non-remanufacturable product rate(F9)	piece/week	Disassembly emission inflow rate(F20)	kgCO2/week
Retreatment rate(F10)	piece/week	Retreatment emission inflow rate(F21)	kgCO2/week
"Remanufacturable product" should satisfy rate(F11)	piece/week	Remanufacturing emission inflow rate(F22)	kgCO2/week

ISSN: 2414-1895 DOI: 10.6919/ICJE.202607_12(7).0004

(1) Collector carbon emission equations

Collector total carbon emissions =Carbon emissions from treatment

(2) Remanufacturer carbon emission equations

Remanufacturer total carbon emissions=Carbon emissions from disassembly
+Carbon emissions from retreatment
+Carbon emissions from remanufacturing

4. Data Analysis

Table 2. Setting for parameters

Parameter	Value	Parameter	Value
Remanufactured product price	1500	Inspection time(T5)	4
Purchase price	200	Treatment time(T6)	4
Holding cost of remanufactured products	10	Purchasing time(T7)	4
Holding cost of "remanufacturable products"	2	Disassembly time(T8)	4
Holding cost of remanufacturable parts	3	Retreatment time(T9)	4
Holding cost of non-remanufacturable products	1	Adjust time of S4(T10)	5
Revenue from retreatment	5	Remanufacturing time(T11)	4
Remanufacturing cost	80	Cover time of S4(T12)	4
Disassembly cost	20	Smooth time2(T13)	4
Transportation cost	2	Sale time(T14)	4
Inspection cost	5	Sold new products(A1)	3000
Holding cost of collected products	2	Using period(A2)	45
Holding cost of "non-remanufacturable products"	1	Required used products per remanufactured product(A9)	1
Revenue from treatment	5	Remanufacturable parts per used product(A10)	1
Collection cost	50	Remanufactured products per part(A11)	1
Collecting time(T1)	4	MinV (A12)	800
Adjust time of S2(T2)	4	MaxV (A13)	1000
cover time of S2(T3)	4	standard D(A14)	10000
Smooth time1(T4)	4	meanV(A15)	900
		seedV (A16)	500

The manufacturer launches new products to the market. It achieves stable weekly sales of 3000 units through distribution channels. This corresponds to an annual sales volume of 156000 units. Partial product loss or non-collection is considered, the actual annual volume is 100000 units. Reference is made to the Remanufacturing-Guidelines for life cycle cost analysis of mechanical products and empirical lifecycle survey data of consumer electronics as well as small-to-medium auto parts. The product is defined with a 52-week service life. After 45 weeks of usage, it gradually enters the used product collection phase. Five scenarios are designed considering changes in the remanufacturing rate. To enable the model to better fit actual demands and reflect the uncertainty of the real market, the RANDOM NORMAL (min, max, mean, variance, seed) function in Vensim is used in the simulation. Parameters are designed based on the capacity assumption of an annual processing volume of 100000 units (equivalent to 2000 units per week), informed by the fluctuation data of automotive parts collection volumes and the established recovery patterns within the remanufacturing industry. Parameter settings are presented in Tables 2. In all figures, the subscript notation is as follows: current denotes $q_r = 0$, q_r2 denotes $q_r = 0.2$, q_r4 denotes $q_r = 0.4$, q_r6 denotes $q_r = 0.6$, and q_r8 denotes $q_r = 0.8$.

According to China Automotive Parts Remanufacturing Market Trends and Prospects Analysis Report (2025), the average collection cost for automotive parts in China is between CNY 40 and 60 per unit. Therefore, this study uses a cost of CNY 50 per unit to match real industry conditions. For retreatment revenue, we referenced actual data from Tianjin Sanyilangzhong Environmental Technology Co., Ltd., which reported CNY 5-6 per unit from scrap processing. Industry standards also show that collection revenue from materials like metals and plastics typically ranges from CNY 3 to 8 per unit. Therefore, this study sets this parameter at CNY 5 per unit. Regarding the selling price of remanufactured products, considering the market pricing characteristics of mid-range automotive parts remanufacturing, it is set at CNY 1500 per unit. For cost parameters, Disassembly and remanufacturing costs were determined by fully considering actual industry labor costs and equipment depreciation, set at CNY 20 per unit and CNY 80 per unit respectively. This objectively reflects core production cost inputs within the remanufacturing process. Inventory holding costs are set differently for each type. Remanufactured goods have the highest cost due to their high value. Non-remanufacturable products have the lowest. This method follows standard logic for managing reverse supply chain inventory.

This study focuses on low-carbon development in auto parts remanufacturing. Meng et al[13]. defined the carbon emission accounting boundary for engine remanufacturing using the lifecycle assessment method. The calculation follows China's General Rules for Carbon Footprint Accounting of Remanufactured Electromechanical Products and uses detailed emission factors from the Carbon Emission Accounts & Datasets (CEADs). For an annual processing capacity of 100000 units (2000 units weekly), and accounting for losses in different stages, the resulting carbon emissions per unit product and the maximum carbon emission target are presented in Table 3.

Table 3. Carbon emissions of each process

Process	Emissions per Unit Product ($kgCO_2e$)	Maximum Carbon Emission Target ($kgCO_2e$)
Treatment	2.5(C1)	1400×2.5=3500
Disassembly	1.2(C2)	1000×1.2=1200
Retreatment	3.5(C3)	750×3.2=2400
Remanufacturing	4.5(C4)	600×4.5=2700

The data was calculated based on standard industry production cycles. The calculation logic aligns with the Guidelines for Greenhouse Gas Emission Accounting and Reporting for Enterprises. This study only considers the carbon emissions generated by the collector during the treatment stage. The impact of different remanufacturing rates (q) of waste products on the collector's carbon emissions is shown in Figure 3.

Volume 12 Issue 7, 2026
DOI: 10.6919/ICJE.202607_12(7).0004

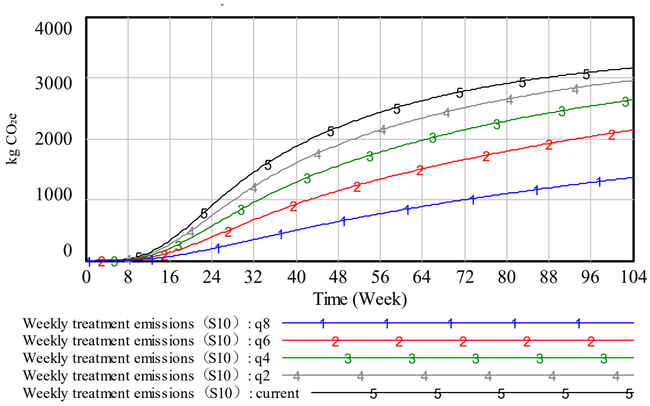

Figure 3. Weekly treatment emission

As shown in Figure 3, the collector's weekly carbon emissions decrease with an increase in q. This reduction occurs because a larger fraction of the collected products are classified as "remanufacturable products" and transferred to remanufacturers. As a result, the volume of "non-remanufacturable products" requiring treatment by the collector is reduced, leading to lower emissions. Due to a maximum weekly carbon emission limit of 3500 kg CO2e for the treatment stage, all emission curves eventually stabilize.

The remanufacturer's weekly carbon emissions consist of three parts: weekly carbon emissions from the disassembly , the retreatment, and the remanufacturing. The carbon emission changes are shown in Figure 4.

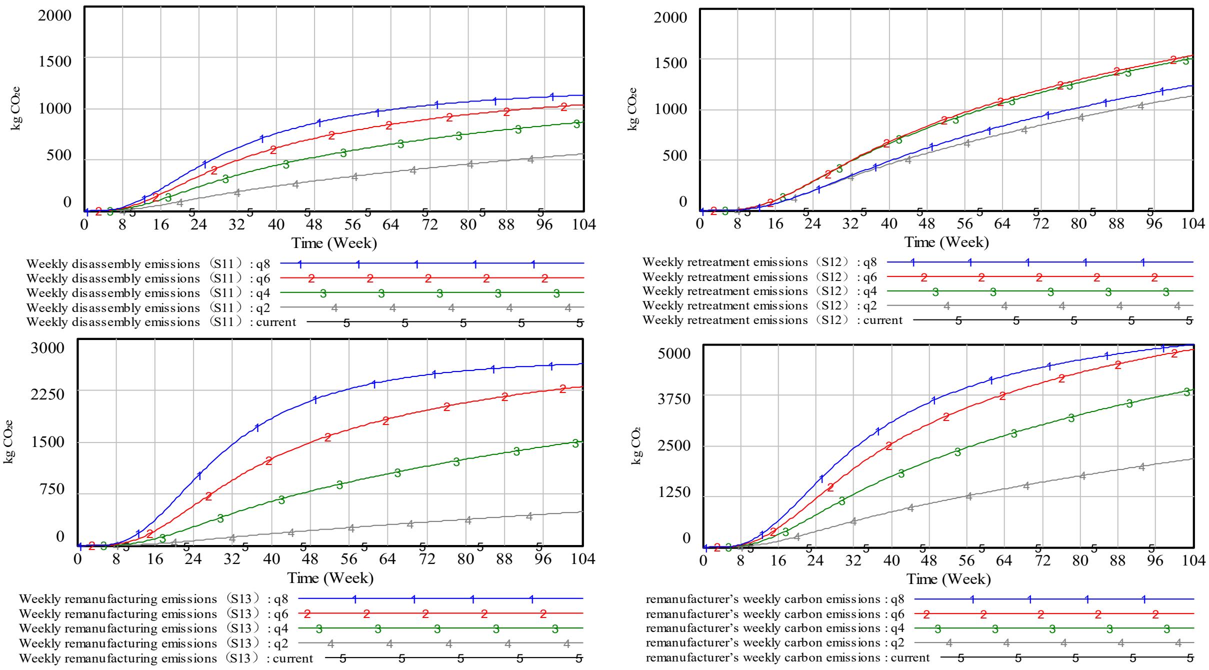

Figure 4. Weekly disassembly, retreatment, remanufacturing emission and remanufacturer' total emission

The remanufacturer's carbon emissions from the disassembly and remanufacturing increase as q_r rises. This correlation exists because higher remanufacturing rate lead to more "remanufacturable products" entering these processes. However, the situation in the retreatment is more complex. At remanufacturing rates of $q_r = 0.2$ and $q_r = 0.8$, carbon emissions are relatively low. In contrast, at intermediate remanufacturing rates of $q_r = 0.4$ and $q_r = 0.6$, emissions are significantly higher.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202607_12(7).0004

This pattern is determined by the fundamental relationship: $F9 = F8 \times (1 - q_r)$, where $F9$ represents the non-remanufacturable product rate and $F8$ denotes the disassembly rate. At a minimal remanufacturing rate, the collected products show a high non-remanufacturing rate. However, the quantity of “remanufacturable products” within the collected stream remains limited. Consequently, the volume requiring retreatment is reduced, resulting in lower emissions. At a maximum remanufacturing rate, although the collected products contain numerous non-remanufacturable items, the non-remanufacturing rate is substantially decreased. Furthermore, many collected “remanufacturable products” accumulate in inventory without undergoing treatment. Therefore, carbon emissions remain at a suppressed level. At intermediate remanufacturing rate, a relative balance is achieved between the remanufacturing rate and the quantity of non-remanufacturable products. The appropriate number of “remanufacturable products” matches the suitable rate, resulting in an efficient remanufacturing process and a correspondingly higher level of carbon emissions. Due to the preset carbon emission target, once the remanufacturing process begins (i.e., $q_r \neq 0$), the system will always converge to the same stable value regardless of how q_r changes.

The remanufacturer’s total carbon emissions are the sum of emissions from disassembly, retreatment, and remanufacturing. Influenced by energy consumption, transportation, sorting, and time costs, the system exhibits a pattern of diminishing marginal carbon reduction. That is, as q_r increases, the incremental growth in carbon emissions from disassembly and remanufacturing decreases. The change of remanufacturer’s total carbon emissions is shown in the figure. Initially, carbon emissions increase as the value of q rises, but as the remanufacturing rate increases, the curve flattens out earliest.

In summary, carbon emissions from collector and remanufacturer exhibit distinct trends across different remanufacturing rate (q_r), depending on the different stages. A higher remanufacturing rate implies that more used products enter the recycling market. However, excessively pursuing a high remanufacturing rate may lead to market imbalance, increased costs, and potential environmental risks. When a carbon emission cap is imposed on firms, an excessively high remanufacturing rate can cause companies to reach their emission peak prematurely. Consequently, subsequent production activities cannot proceed as originally planned. Therefore, for both collector and remanufacturer, maximizing profitability requires not only relying on the remanufacturing rate but also accounting for carbon emission constraints. To address this, carbon reduction investment is introduced next. Such investment aims to decrease the carbon emissions per unit product across the treatment, disassembly, retreatment, and remanufacturing stages. Its effect on the profits of both collector and remanufacturer will be discussed.

5. Profit Optimization Strategy under Carbon Emission Reduction Investment

5.1 Problem Description

The Implementation Plan for Science and Technology Support of Carbon Peaking and Carbon Neutrality in Tianjin mentions advancing low-cost, low-energy-consumption carbon dioxide capture technologies, as well as low-cost, large-scale carbon dioxide chemical and biological utilization technologies. It calls for organizing fundamental research on CCUS and advanced predictive management for carbon neutrality. Focusing on clean energy, advanced power grids, and carbon reduction in key sectors, the plan will implement key research and development programs and major science and technology initiatives. This strongly aligns with research by Zhao et al.[14], Their study on offshore vessels showed that OCCUS technology achieves an 81.22% carbon reduction rate.

In the reverse supply chain of remanufacturing, the application of CCUS (Carbon Capture, Utilization, and Storage) technology primarily focuses on two key areas: carbon capture and carbon utilization. As a large-scale greenhouse gas reduction technology, it represents China's sole technical option for low-carbon utilization of fossil energy and is an indispensable key technology supporting the goals of carbon peaking and carbon neutrality. Treatment, retreatment, and remanufacturing emissions represent high-concentration sources (>10% CO_2e), with reduction potentials ranging from 70% to

ISSN: 2414-1895 DOI: 10.6919/ICJE.202607_12(7).0004

90%. Disassembly processes constitute medium-concentration sources (3%-10% CO_2e), offering reduction potentials between 50% and 70%.

This study assumes that both collector and remanufacturer invest in carbon reduction measures to lower per-unit carbon emissions during product treatment, disassembly, retreatment, and remanufacturing. It thoroughly examines how to maximize profits for collector and remanufacturer under varying product remanufacturing rates, balancing economic and environmental benefits, and proposes corresponding strategic choices. Comprehensively evaluating capture, transportation, and storage costs across the entire CCUS chain, Annual Report on Carbon Capture, Utilization and Storage (CCUS) in China (2024) indicates that the average capture cost for domestic CCUS projects ranges from CNY 200 to 300 per ton of CO_2e. To achieve a 60% reduction across the entire process, each product must reduce emissions by $(C1 + C2 + C3 + C4) * 0.6 = 6.84\ \mathrm{kg}\ CO_2e$. Thus, the minimum cost per product for achieving this reduction is CNY 1.368. As stronger emission reduction capabilities incur higher additional energy costs, the adjusted relationship between carbon reduction investment per unit product and reduction efficiency is set as follows: investing CNY 1 achieves 60% reduction; investing CNY 2 increases reduction to 70%; investing CNY 3 further boosts reduction to 80%. This study simulates different investment scenarios at varying remanufacturing rate. It aims to identify the optimal carbon reduction investment strategies for collectors and remanufacturer, helping them maximize profits. The profit change compares the profit for collector and remanufacturer after investment in carbon reduction to their profit in the non-investment scenario. The specific values are shown in Tables 5 and 6, and collector and remanufacturer profit stock-flow diagram is illustrated in Figure 5

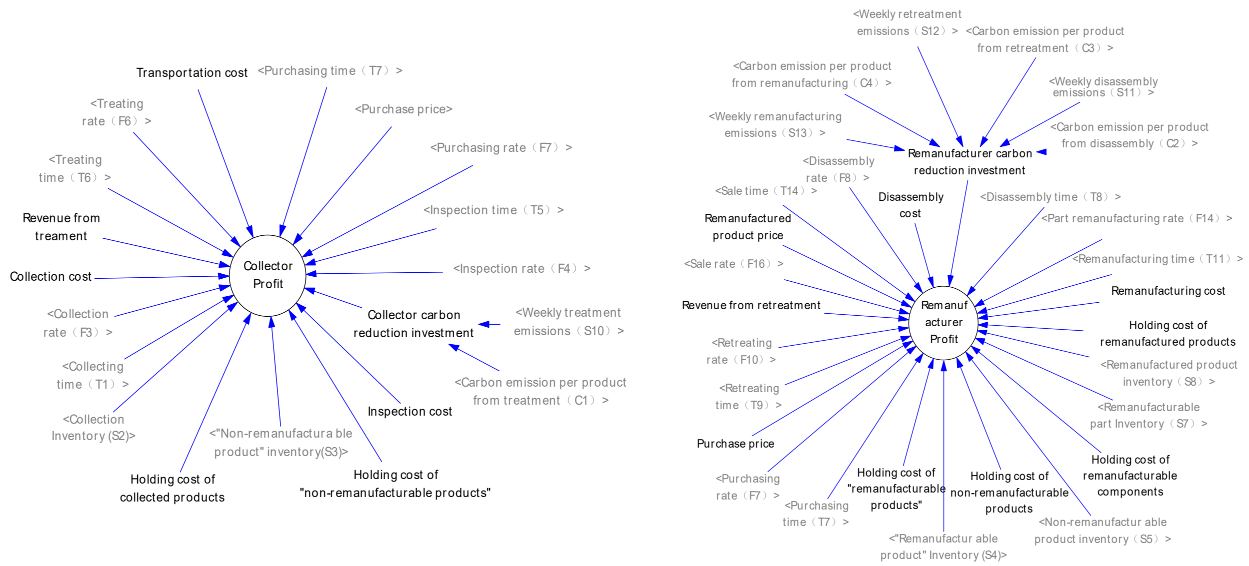

Figure 5. Collector and remanufacturer profit stock-flow diagram

5.2 Relevant Equations

(1) Collector profit=Profit from sales to remanufacturer+Treatment profit

−(Collection cost+Holding cost of collected products+Inspection cost)

−Collector carbon reduction investment

Collector carbon reduction investment= Weekly treatment emissions (S10)

/Carbon emissions per product in treatment (C1)

×Carbon reduction investment per unit product

(2) Remanufacturer profit=(Revenue from remanufactured product sales+Retreatment profit)

−(Purchase cost+Holding cost+Disassembly cost

ISSN: 2414-1895 DOI: 10.6919/ICJE.202607_12(7).0004

+Part remanufacturing cost)
−Remanufacturer carbon reduction investment
Remanufacturer carbon reduction investment=Weekly remanufacturing emissions (S13)
/Carbon emissions per product in remanufacturing (C4)
×Investment per unit +Weekly retreatment emissions (S12)
/ Carbon emission per product from retreatment (C3)
×Investment per unit+ Weekly disassembly emissions (S11)
/ Carbon emission per product from disassembly (C2)
×Investment per unit

Table 4. Collector variations

Remanufacturing Rate	Technology (Percentage Reduction of Carbon Emission)	Carbon Reduction Investment Amount (Unit/CNY)	Profit Change (CNY)
$q_r = 0.2$	**60%**	1	**-848.95**
	70%	2	-1931.04
	80%	3	-2651.83
$q_r = 0.4$	60%	1	2766
	70%	2	**2854.6**
	80%	3	1888.3
$\boldsymbol{q_r = 0.425}$	60%	1	5111.9
	70%	2	**6968.9**
	80%	3	6356.9
$\boldsymbol{q_r = 0.45}$	60%	1	2164.9
	70%	2	2665.7
	80%	3	**3522.6**
$q_r = 0.5$	60%	1	-642.1
	70%	2	4733
	80%	3	**6694.2**
$q_r = 0.6$	60%	1	5605
	70%	2	8951
	80%	3	**13114**
$q_r = 0.8$	60%	1	27038
	70%	2	38622
	80%	3	**53296**

When the remanufacturing rate is notably limited, collector face consistent financial losses. This is because its costs for collecting, inspecting, and treating waste are higher than the revenue from selling "remanufactured products". In this case, collector typically choose either zero- investment, or adopt

 Volume 12 Issue 7, 2026
DOI: 10.6919/ICJE.202607_12(7).0004

a minimal-investment carbon reduction technology (CNY 1 per unit for a 60% emission reduction). This strategy allows them to contain financial losses and enhance profitability.

As the remanufacturing rate q_r increases, within the range of 0.4 to 0.425, medium-level investment options are preferred (CNY 2 per unit for a 70% emission reduction), yielding the highest profit improvement in this interval. Once q_r surpasses 0.425, the majority of collected products become suitable for remanufacturing. At elevated remanufacturing rate, collector favor high-investment carbon reduction technologies (CNY 3 per unit for a 80% emission reduction). This stage also exhibits economies of scale, as q_r continues to rise, profits generated under the high-investment scenario increase correspondingly.

This outcome aligns with real-world dynamics. When the quantity of collected products remains constant, collector can divert an increasing number of products for remanufacturing. Consequently, the volume of "remanufacturable products" sold to remanufacturer grows, while the amount of "non-remanufacturable products" requiring their own processing decreases. Subject to carbon emission constraints during treatment, collector is incentivized to enhance carbon reduction technologies and collect more products, thereby maximizing overall profit. Consequently, the decision threshold for collectors lies between $q_r = 0.425$ and $q_r = 0.45$.

Table 5. Remanufacturer variations

Remanufacturing Rate	Technology (Percentage Reduction of Carbon Emission)	Carbon Reduction Investment Amount (Unit/CNY)	Profit Change (CNY)
$q_r = 0.2$	**60%**	1	**-192.4**
	70%	2	-283.1
	80%	3	-375.3
$\mathbf{q_r = 0.4}$	60%	1	4668.4
	70%	2	**5853.3**
	80%	3	4707.9
$\mathbf{q_r = 0.425}$	60%	1	2154.3
	70%	2	2455.8
	80%	3	**2698.8**
$q_r = 0.45$	60%	1	6344
	70%	2	8979
	80%	3	**9074**
$q_r = 0.5$	60%	1	-600
	70%	2	14626
	80%	3	**17483**
$q_r = 0.6$	60%	1	22195
	70%	2	33167
	80%	3	**42641**
$q_r = 0.8$	60%	1	100432
	70%	2	123502
	80%	3	**146670**

Under a notably constrained remanufacturing rate, remanufacturer can only collect a restricted quantity of “remanufacturable products”. The processing of “remanufacturable products” requires significant investment in materials, time, and other costs. When the volume of remanufactured products produced is not enough and their pricing is insufficiently high, fixed costs may not be adequately amortized. This situation creates scale diseconomies within the reverse supply chain. Consequently, to mitigate losses and enhance profitability, remanufacturer typically adopt either a zero-investment approach toward carbon reduction or select a minimal-investment (CNY 1 per unit for a 60% emission reduction).

When the remanufacturing rate increases, at $q_r = 0.4$, remanufacturer tend to choose medium investment (CNY 2 per unit for a 70% emission reduction), yielding the greatest profit increase at this point. When the remanufacturing rate q_r exceeds 0.425, economies of scale emerge. As q_r increases, remanufacturer achieve higher profits by selecting the high-investment option (CNY 3 per unit for a 80% emission reduction). Therefore, the decision threshold for remanufacturer lies between $q_r = 0.4$ and $q_r = 0.425$. Consequently, the following conclusions are drawn:

Conclusion 1: For both the collector and the remanufacturer, when $q_r \leq 0.2$, it is optimal to make zero-investment or minimal-investment in carbon reduction. Due to the severely limited remanufacturing rate, supply chain members remain in a persistent loss state, and investing in carbon reduction would further reduce profit compared to the baseline. If policy constraints mandate emission reductions, the optimal strategy under such conditions is to reduce collection volume while making zero or minimal investment in carbon reduction.

Conclusion 2: For the collector, when $0.2 < q_r < 0.45$, a medium-level carbon reduction investment is optimal; when $q_r \geq 0.45$, a high-level investment is preferred. Analysis results indicate that within the range $0.425 < q_r < 0.45$, there exists a critical threshold at which the collector’s optimal strategy shifts from medium to high-level investment.

Conclusion 3: For the remanufacturer, when $0.2 < q_r < 0.425$, a medium-level carbon reduction investment is optimal; when $q_r \geq 0.425$, a high-level investment is preferred. Analysis results show that within the range $0.4 < q_r < 0.425$, there exists a critical threshold at which the remanufacturer’s optimal strategy transitions from medium to high-level investment.

According to the profit-driven principle, the collector and remanufacturer make different carbon reduction choices at each stage of the process. Their decisions are strongly influenced by the remanufacturing rate (q_r). When the remanufacturing rate is severely constrained ($q_r \to 0$), elevated collection costs and minimal returns prompt the collector to adopt either a minimal-investment approach (CNY 1 per unit for a 60% emission reduction) or a zero-investment strategy to minimize losses; similarly, the remanufacturer adopts a conservative strategy due to diseconomies of scale. As q_r rises to 0.4, the collector achieves profit maximization through medium-level investment (CNY 2 per unit for a 70% emission reduction), and the remanufacturer also selects medium-level investment (CNY 2 per unit for a 70% emission reduction) to balance cost and benefit. At $q_r = 0.425$, the collector continues with medium-level investment, whereas the remanufacturer switches to high-level investment (CNY 3 per unit for a 80% emission reduction) as the optimal strategy. Beyond $q_r = 0.425$, economies of scale emerge, the collector adopts high-level investment (CNY 3 per unit for a 80% emission reduction) to capture carbon reduction benefits and bargaining advantages, while the remanufacturer maintains high-level investment(CNY 3 per unit for a 80% emission reduction) to realize green premiums and cost optimization. This dynamic decision-making process reveals the synergistic relationship between environmental and economic benefits in the reverse supply chain. Influenced by various factors, the decision thresholds of supply chain members can be adjusted through reverse logistics optimization and policy interventions (e.g., subsidies or carbon pricing), thereby enhancing overall system efficiency. This also provides a theoretical basis for the formulation of differentiated policy measures.

6. Conclusion

This study constructs a system dynamics model for reverse supply chains targeting the continuous improvement of carbon emission reduction capacity. Through data analysis and multi-scenario decision optimization analysis, it explores the changes in carbon emissions and the selection of carbon emission reduction investment strategies under different remanufacturing rates. The following core conclusions and targeted strategy recommendations are as follows:

(1) The dynamic impact mechanism of remanufacturing rate on carbon emissions serves as the decision-making foundation for enhancing carbon emission reduction capacity.

The study finds that carbon emissions across various stages of the reverse supply chain exhibit a significant dynamic correlation with the remanufacturing rate. Carbon emissions from collector's treatment show a monotonically decreasing trend as the remanufacturing rate increases. In contrast, carbon emissions from remanufacturer's disassembly and remanufacturing present a monotonically increasing trend with the rise in remanufacturing rate. Carbon emissions from retreatment display non-linear characteristics, peaking at a medium remanufacturing rate. This reflects the dynamic balance between resource recycling efficiency and production energy consumption. This non-linear impact mechanism indicates that the improvement of carbon emission reduction capacity cannot be achieved through a single strategy. It must be premised on the quantitative evaluation of remanufacturing rate to construct differentiated emission reduction paths.

(2) Carbon emission reduction investment decisions exhibit a phased threshold characteristic and serve as a key lever for enhancing carbon emission reduction capacity.

The study finds that the carbon emission reduction strategy choices for both the collector and the remanufacturer is closely related to remanufacturing rate q. Based on data simulation, to achieve the dual goals of “optimal cost + maximum emission reduction”, three phased adaptive emission reduction strategies are proposed:

Strategy 1: Conservative carbon reduction under constrained remanufacturing rate. When $q \leqslant 0.2$, the marginal cost of reduction remains elevated, rendering zero or minimal investment the optimal choice, which can avoid the damage to supply chain economic benefits caused by over-investment.

Strategy 2: Balanced emission reduction strategy for the medium remanufacturing rate interval. When the remanufacturing rate falls within the critical range (collector:$0.2<q<0.45$; remanufacturer: $0.2<q<0.425$) emission reduction investment begins to generate economies of scale. Through medium level investment, the synergistic maximization of carbon emission reduction benefits and profits can be achieved.

Strategy 3: Aggressive carbon reduction under elevated remanufacturing rate. When the remanufacturing rate exceeds the critical threshold (collector:$q \geqslant 0.45$; remanufacturer: $q \geqslant 0.425$), elevated investment becomes an inevitable choice to achieve a leapfrog improvement in carbon emission reduction capacity and establish competitive advantages. This decision-making mechanism stems from the cooperative effect of economies of scale and carbon emission reduction dividends.

This study aims to optimize the low-carbon operation of reverse supply chains by enhancing the carbon emission reduction capacity of supply chain members, thereby achieving dual breakthroughs at both theoretical and practical levels. At the theoretical level, it reveals the dynamic regulatory mechanism of remanufacturing rate on carbon emission reduction strategies. It then clarifies the change law of carbon emission reduction effects under different remanufacturing rate scenarios and fills the research gap in the long-term behavioral study of carbon emissions in reverse supply chains. Furthermore, it provides a new analytical perspective for the in-depth application of carbon emission reduction theories in the reverse supply chain field. At the practical level, based on the relationship between carbon emission reduction marginal benefits and remanufacturing rate, it proposes phased carbon emission reduction investment strategies. These strategies act as a dynamic decision-making tool for enterprises and help accurately improve carbon emission reduction efficiency. They also guide enterprises to optimize operational decisions under carbon constraints. Meanwhile, they

Volume 12 Issue 7, 2026
DOI: 10.6919/ICJE.202607_12(7).0004

provide a quantitative basis for policymakers. Policymakers can use this basis to design dynamically differentiated incentive policies (e.g., progressive carbon tax, carbon emission reduction subsidies). This further facilitates the implementation of carbon emission reduction goals. Future study can consider the overall collaborative carbon emission reduction of supply chains, expand the number of supply chain members to form a multi-level remanufacturing reverse supply chain, and introduce key factors such as consumers' green preferences and carbon policy constraints. This will improve the model's practical applicability to carbon emission reduction practices and provide more realistic theoretical support and practical guidance for the continuous enhancement of carbon emission reduction capacity in reverse supply chains.

References

[1] Kong, Y., Liu, J., & Chen, J. (2023). Exploring the carbon abatement measures in maritime supply chain: A scenario-based system dynamics approach. *International Journal of Production Research*, *61*(18), 6131–6152.

[2] Gu, Q. L., & Gao, T. G. (2017). IERs in reverse supply chain: Be worth lowering or not. *Computers & Industrial Engineering*, *111*, 289–302.

[3] Pazouki, M., Jaber, M. Y., & Afshari, H. (2025). Linking forward and backward product quality in a manufacturing/remanufacturing inventory system with price-quality-dependent demand and return rates. *Computers & Industrial Engineering*, *204*, 111072.

[4] Long, X. F., et al. (2017). Strategy analysis of recycling and remanufacturing by remanufacturers in closed-loop supply chain. *Sustainability*, *9*(10), 1818.

[5] Ullah, M. (2023). Impact of transportation and carbon emissions on reverse channel selection in closed-loop supply chain management. *Journal of Cleaner Production*, *394*, 136370.

[6] Zhou, Y., Lin, X. T., Fan, Z. P., & Wong, K. H. (2022). Remanufacturing strategy choice of a closed-loop supply chain network considering carbon emission trading, green innovation, and green consumers. *International Journal of Environmental Research and Public Health*, *19*(11), 6782.

[7] Zhang, L. H., Dong, K., & Zhang, R. (2019). Strategic choice analysis for supply chain in 'cap and trade' system and carbon emission reduction technology. *Chinese Journal of Management Science*, *27*, 63–72.

[8] Gu, Q. L., & Gao, T. G. (2012). Joint decisions for R/M integrated supply chain using system dynamics methodology. *International Journal of Production Research*, *50*(16), 4444–4461.

[9] Vlachos, D., Georgiadis, P., & Iakovou, E. (2007). A system dynamics model for dynamic capacity planning of remanufacturing in closed-loop supply chains. *Computers & Operations Research*, *34*(2), 367–394.

[10] Mutingi, M. (2014). The impact of reverse logistics in green supply chain management: A system dynamics analysis. *International Journal of Industrial and Systems Engineering*, *17*(2), 186–201.

[11] Golroudbary, S. R., & Zahraee, S. M. (2015). System dynamics model for optimizing the recycling and collection of waste material in a closed-loop supply chain. *Simulation Modelling Practice and Theory*, *53*, 88–102.

[12] Luo, R., Fan, T., & Xia, H. (2014). The game analysis of carbon reduction technology investment on supply chain under carbon cap-and-trade rules. *Chinese Journal of Management Science*, *22*(11), 44–53.

[13] Meng, Q. Y., et al. (2023). Research on carbon emission reduction assessment of automobile engine remanufacturing. *China Auto*, (05), 10–15.

[14] Zhao, Y. Z., et al. (2025). Onboard carbon capture, utilization and storage (CCUS) supply chain optimization: An application to vessels active in the offshore wind industry. *Energy Conversion and Management*, *348*, 120640. https://doi.org/10.1016/j.enconman.2025.120640