

An Effective Three-Echelon Reverse Supply Chain Strategic Alliance under Cap-and-Trade Regulation

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Abstract—In recent years, the booming industry has led to the extensive development of petrochemical energy, coupled with extensive deforestation, resulting in more serious global warming. Climatic anomalies around the world have made it an imperative for enterprises to effectively limit carbon emissions to protect the environment.

In the study, we incorporate carbon emission reduction with implementing corporate social responsibility into a three-echelon reverse supply chain for used products. Assumed that carbon emission depends on sustainability level and the returns (used products) quality is stochastic. The optimization recycling models for both decentralized and centralized systems are formulated and then compared to each other. The results show that the centralized system can achieve higher profits and has lower carbon emissions.

This study contributes by: (i) developing closed-loop supply chain models with recycler–manufacturer–retailer interactions for reused products; (ii) incorporating both cap-and-trade regulation and green technology investment as emission-reduction mechanisms; (iii) modeling demand as dependent on price and technology level under decentralized and centralized structures; and (iv) providing comparative insights on profits, emissions, and sensitivity, with directions for multi-agent extensions.

A computing software Maple 18 has been developed for this purpose and is implemented to derive the optimum decision for each player. Numerical examples and sensitivity analyses are given to illustrate the results.

Keywords— Cap-and-trade; Corporate social responsibility; re-manufacturing; Green technology.

1. Introduction

As the world rapidly moves toward industrialization, urbanization, and population growth, both the economy and society are booming. In the process of vigorous economic and social development, due to the large-scale mining and use

of fossil fuels and the development and use of various chemical products, emitting a large amount of carbon dioxide (CO₂) and other greenhouse gas (GHG). Before the industrialization period, the atmosphere the CO₂ concentration has remained stable at about 280 ppm, and has now increased significantly to more than 420 ppm, and continues to rise, under the influence of large amounts of anthropogenic GHG emissions, the global average annual temperature has increased by 1.1°C, resulting in heavy rainfall, Droughts, heat waves, severe cold and other extreme climate phenomena occur frequently and give rise to other environmental and social problems. Climate change has caused serious economic losses and even threatened the safety of life and property. It is the most serious environmental issue currently. one of the environmental issues (IPCC, 2007) [1].

GHG emissions or reductions taken anywhere in the world contribute to policies not only affect the local climate system, but also the global climate system, thus maintaining the climate system. GHG comes from economic activities such as the use of fossil fuels, industrial processes, food production, and animal husbandry. Reducing GHG emissions involves the interests of all countries.

After the entry into force of the "Kyoto Protocol" on Feb. 16, 2005, the United Nations and Member States not only paid more attention to environmental issues and positive effects of the greenhouse effect, but also increased carbon dioxide emissions (Carbon Cap-and-Trade) actively promotes and establishes a carbon trading market. After the rise in carbon trading in the international trading market, it has brought huge business opportunities. Unlike the securities or financial derivative goods that can be traded solely, the carbon emissions of private enterprises supply and demand are used as transactions, but they are similar. Commodity futures can be listed. and traded in major international securities or commodity exchanges in the future. It is not only the policy and goal of international environmental protection, but also the plans for emission reduction

in the future global countries. The market has great room for growth. Carbon trading can predict and determine development costs and development risks based on the company's sustainability capabilities and market trends.

Therefore, companies should be encouraged to carry out greenhouse gas reductions early, obtain appropriate investment returns through carbon rights trading, and act as specific policies for greenhouse gas reduction. In this paper, we focus on analysing the strategy of supply chain management under the constraint of cap-and-trade regulation and investment in green technology. In early 2009, Exxon Mobil Chairman and CEO Rex Tillerson issued a statement of support advocated a carbon tax rather than an emissions trading system because he believed a carbon tax was more direct, transparent and Effective ways to reduce GHGs.

In recent years, the rapid growth of product returns and the tightening of environmental regulations have drawn increasing attention to reverse supply chain management. Particularly, the cap-and-trade mechanism has become one of the most widely adopted regulatory tools for controlling carbon emissions across industries. Under this mechanism, firms are not only required to manage their operational efficiency but also to balance carbon allowances and potential trading activities. For reverse supply chains, which involve recyclers, manufacturers, and retailers, this regulation introduces both challenges and opportunities. On the one hand, operational processes such as collection, remanufacturing, and redistribution often generate significant carbon emissions, requiring firms to adopt greener technologies and optimize logistics. On the other hand, effective coordination among different supply chain members can reduce costs, improve recovery efficiency, and even create competitive advantages in low-carbon markets.

This paper examines an effective three-echelon reverse supply chain strategic alliance, consisting of a recycler, a manufacturer, and a retailer, under cap-and-trade regulation. The study focuses on how such alliances can align their objectives to maximize joint profits while simultaneously reducing carbon emissions. By forming strategic partnerships, members can coordinate decisions on pricing, collection rates, and technology investments, ensuring not only compliance with emission caps but also enhanced competitiveness in sustainable markets. The findings are expected to provide practical guidance for firms seeking to integrate environmental responsibility into their business strategies while maintaining profitability in the era of carbon-constrained economies.

2. LITERATURE REVIEW

Yang et al. examined how a cap-and-trade (carbon) regulation affects the choice of collection mode (manufacturer collection, retailer collection, or third-party) in a remanufacturing/closed-loop supply chain. The authors build analytical Stackelberg/Stackelberg-type models with and without remanufacturing, incorporate emission constraints and carbon trading costs, and compare profits, emissions, and collection rates under alternative collection assignments. Main findings: remanufacturing can simultaneously improve emission reduction and firm profitability under certain parameterizations; cap-and-trade changes the relative desirability of collection modes and can alter who (manufacturer vs retailer vs third party) should optimally manage returns. This paper is often cited in the literature linking environmental regulation (cap-and-trade) with reverse-channel strategy [2].

Kaur presented how green product design and institutional pressures affect the performance of manufacturing firms in Malaysia through the implementation of reverse logistics for products. The research likely situates reverse logistics within broader environmental and institutional frameworks [3]. Kannan and Gholizadeh addressed design of a robust, sustainable and resilient reverse logistics network (RLN) for end-of-life vehicles (ELVs). The authors propose a multi-objective robust optimization model that incorporates big-data-driven demand/return uncertainty and resilience criteria (e.g., disruption scenarios). They apply the model to an ELV case study to show trade-offs between cost, environmental impact, and resilience measures, and demonstrate how robust planning reduces vulnerability to uncertainty while supporting sustainability goals. The work is notable for integrating big-data estimations with robust multi-objective location-allocation decisions for reverse flows [4].

Hussein and Othiambo positioned reverse logistics as a key component of circular economy strategies within industrial performance analysis [5]. Kumar investigated the significance of the green supply chain, particularly during and since the COVID-19 pandemic. By reviewing current literature, it addresses elements of sustainable supply chain management—including reverse logistics—and outlines their growing relevance amid global disruptions [6]. Cao et al. focused on the interaction between Extended Producer Responsibility (EPR) regulation and the real-world presence of secondary (used goods) markets, this paper develops analytical models to examine firms' decisions to recover and remanufacture returned products. The authors quantify how EPR policies alter collection rates, remanufacturing incentives, and producer profits when a secondary market

competes with remanufactured offerings. Results indicate that appropriate EPR design can encourage higher recovery and remanufacturing rates, but secondary-market competition can weaken firms' incentives — a tension the paper analyzes to propose policy and managerial adjustments [7].

This systematic literature review synthesizes research on both forward and reverse logistics as enablers of circular economy practices in the construction sector. The paper collates studies on collection, reuse/recycling of construction and demolition waste, reverse-logistics network design for bulky materials, barriers/drivers, and enabling technologies (e.g., IoT, digital twins). The review identifies research gaps (e.g., limited empirical evidence on cost-effective reverse systems for large-scale construction flows), highlights best practices for integrating reverse logistics into construction supply chains, and proposes future research directions to operationalize circularity in heavy/fragmented supply chains. Given Journal of Cleaner Production's influence, this review is a useful high-level roadmap for academics and practitioners working on reverse supply chains in resource-intensive sectors [8].

He et al. proposed a hybrid closed-loop supply chain (CLSC) model in which end-of-life (EOL) product collection is contested among different collector types (manufacturer, retailer, third-party). The authors construct a game-theoretic CLSC model covering monopoly, duopoly, and mixed competition among collectors and propose new "collection convenience" functions to capture customer preferences and distrust toward specific collectors. Using analytical modelling and comparative analysis, the study shows how collection competition and customer channel preferences affect pricing, convenience investments, total collection rates, and the split of recovered products between remanufacturing and recycling. Key findings stress that the most preferred collector's strategy often dominates total collection outcomes and that customer distrust reduces players' incentives and alters recovery efficiency [9].

Kuno & Arani investigated the relationship between reverse logistics and the performance of plastic bottling firms in Mombasa County, Kenya. Using a cross-sectional design, the research examines how practices like reuse, recycling, remanufacturing, and repackaging influence firm performance. Data were collected using structured questionnaires and analysed using descriptive and inferential statistics, including hierarchical moderated multiple regression [10].

Haites (2018) focused on 17 emissions trading systems and 18 carbon tax systems that had been implemented in 55 jurisdictions around the world as of 2015. Finally, they conducted an effectiveness analysis to help policymakers make decisions [9].

Currently the international discussions on carbon pricing mechanisms mostly focus on levying carbon taxes or implementing emissions trading and matching offset mechanisms. The reduction measures adopted in voluntary reductions are divided into two types of measures: emission reduction/avoided emissions and carbon removal. But carbon removal has a key advantage over emissions reduction measures because carbon removal technology can remove emissions from the atmosphere, so they will ultimately play an extremely important role in stabilizing atmospheric CO₂ concentrations and may even reduce concentrations after net-zero emissions are achieved [11].

Xu et al. (2023) uses a multi-regional environment dynamic calculation general equilibrium model (dynamic computable general equilibrium model) to explore the costs of implementing carbon tax and emissions trading in China and two different economic regions. Efficiency, the results show that emissions trading is better than carbon tax in terms of economic development because emissions trading will generate lower economic cost [12].

Mandal & Mohammed explored how artificial intelligence (AI) can be implemented in transportation routing within reverse logistics to reduce CO₂ emissions. By optimizing routing processes, it aims to enhance logistics efficiency while minimizing environmental impact. The research further examines the intersection of technological innovation and environmental economics in shaping sustainable practices [13].

The authors propose a machine-learning counterfactual construction to evaluate the UK carbon price support (a carbon tax on power plants) and other schemes. Using this modern policy-evaluation approach they estimate emissions and cost impacts while addressing control-group selection. They find measurable emissions reductions from carbon pricing and show how ML counterfactuals can sharpen ex-post policy inference [14].

This analytical paper studies the policy design problem when a government can set a carbon tax and/or a subsidy for carbon dioxide removal (CDR) but faces inter-regional leakage of emissions. Using a theoretical model, they show the optimal CDR subsidy need not equal the carbon tax because of leakage and terms-of-trade effects; for many realistic parameterizations the optimal CDR subsidy exceeds the carbon tax. The paper highlights strategic differences between carbon taxes and removal subsidies in an open world [15].

Finkelstein-Shapiro & Metcalf used a quantitative general equilibrium model with search-friction labor markets and endogenous firm entry and green-technology adoption, the authors estimate macro and labor-market effects of a carbon tax

calibrated to hit U.S. Paris targets. Key findings: when technology adoption and firm creation are endogenized, a carbon tax that achieves large emission cuts can have mildly positive long-run effects on consumption and output and can expand green-technology adoption; ignoring these margins can overstate short-term costs [16].

This empirical paper uses synthetic-control and related quasi-experimental methods to estimate California's cap-and-trade impacts by sector. Results show clear reductions in power-sector emissions (largely due to the power mix shift to renewables) but mixed or limited declines in the industrial sector, suggesting complementary policies and sectoral context are critical for cap-and-trade effectiveness. The study provides sectoral nuance to policy evaluation of emissions trading [17].

Using firm-level data and difference-in-differences with propensity-score matching, the authors evaluate India's Perform-Achieve-Trade (PAT) scheme (an energy-efficiency cap-and-trade program). They find no robust positive effect on measured energy efficiency across firms but detect adverse effects on firm market value in some specifications—pointing to distributional and competitiveness channels that merit careful design and revenue/compensation rules [18].

This randomized, incentivized experiment on a representative German sample compares voter support for several revenue-recycling schemes (uniform dividend / per-capita transfers, green investments, targeted rebates). Main finding: uniform carbon dividends or clearly framed immediate transfers raise public approval markedly compared to vague uses of revenue — a clear behavioral insight for politically viable carbon taxes [19].

Introduction (content): Using game-theoretic modelling, this paper studies combined policy mixes (carbon quotas / cap-and-trade and production subsidies) and their strategic interactions with firms' production and abatement choices. The analysis provides comparative insights into when cap-and-trade plus subsidies can yield welfare-improving outcomes and when they create perverse incentives — useful for designing complementary climate policy packages [20].

3. MATHEMATICAL MODEL

3.1 ASSUMPTIONS AND NOTATIONS

The mathematical model in this study is based on the following assumptions:

- (1) In this model, the acceptance level of collected returns is represented by l , which is determined by $S_c = S_0 \cdot l^2$. The expression

shows that the unit screening cost is a non-linearly increasing function of the acceptance level.

- (2) All recovered quantities are screened by the recycler and the qualified quantity is given to the remanufacturer.
- (3) we assume that the sustainability investment cost for the manufacturer is a quadratic function, i.e., $\frac{1}{2} \eta s^2$, where η is the sustainability investment coefficient.
- (4) The pricing of remanufactured products is affected by the pricing of new products.
- (5) Remanufactured products can be sold out to meet market demand.

The following notations are used in this study:

p_r : Purchase cost (\$/unit)

θ : The price of return item as a fraction of wholesale price (\$/unit)

s_p : Scrap cost (\$/unit)

l : The acceptance level

s_c : Screening cost (\$/unit)

D : Market demand, $D(s, p_1, p_2) = D_0 + \alpha s - \beta p_1 + \gamma p_2$

p_2 : The given price of all new item (\$/unit)

e_1 : Carbon emissions per unit in remanufacturing stage

e_2 : Carbon emissions per unit in holding stage

b_1 : Parameter of the green technology effect (remanufacturing)

b_2 : Parameter of the green technology effect (holding)

K : Carbon emission cap

η : Sustainability investment coefficient

c_e : Unit carbon emissions trading price (\$/unit)

c_m : Unit remanufacturing cost (\$/unit)

h_m : Unit holding cost for remanufacturer (\$/unit/unit time)

h_r : Unit holding cost for retailer (\$/unit/unit time)

h_b : Unit holding cost for recycler (\$/unit/unit time)

w : Wholesale price (\$/unit) (decision variable)

s : Sustainability level (decision variable)

p_1 : The price of remanufacturing item (\$/unit) (decision variable)

3.2 Analysis of the decentralized system

In the decentralized system, the recycler, the remanufacturer and retailer make their decisions separately to maximize their own profits. We consider the decentralized case where the manufacturer is a Stackelberg leader and the others are followers. The sequence of events is: The remanufacturer first determines the wholesale price and the sustainability level to maximize her total profit per time unit; then, the retailer and the recycler, as the followers, determine the selling price and the acceptance level to maximize their total profit per time unit respectively. For a given wholesale price w , the profit function of the retailer includes the sales revenue, purchasing cost and

holding cost. Hence, the total profit per time unit of the retailer is

$$\prod_R(p_1) = p_1 \cdot D(s, p_1, p_2) - w \cdot D(s, p_1, p_2) - \frac{h_r}{2} \cdot D(s, p_1, p_2) \quad (1)$$

In this model, the acceptance level of collected returns is represented by l , which is determined by $s_c = s_0 \cdot l^2$. The expression shows that the unit screening cost is a non-linearly increasing function of the acceptance level.

$\pi_M(s, w)$ As the follower of the Stackelberg game, for a given wholesale price w and market demand D , the profit function of the recycler includes the sales revenue, purchasing cost, holding cost, screening cost and scrap cost. Hence, the total profit per time unit of the recycler is

$$\prod_R(l) = w\theta \cdot D(s, p_1, p_2) - \frac{p_r}{l} \cdot D(s, p_1, p_2) - \frac{s_c(l)}{l} \cdot D(s, p_1, p_2) - \frac{s_p \cdot (1-l)}{l} \cdot D(s, p_1, p_2) \quad (2)$$

we assume that the sustainability investment cost for the manufacturer is a quadratic function, i.e., $\frac{1}{2}\eta s^2$, where η is the sustainability investment coefficient.

The profit per production cycle of the remanufacturer under cap-and-trade regulation includes the sales revenue, production cost, holding inventory cost, investment in green technology, and revenue (cost) from selling (buying) the extra carbon emission permits. Hence, we express the total profit per time unit of the remanufacturer as

$$\prod_M(s, w) = w(1-\theta) \cdot D(s, p_1, p_2) - c_m \cdot D(s, p_1, p_2) - \frac{h_m}{2} \cdot D(s, p_1, p_2) - \frac{h_b}{2} \cdot D(s, p_1, p_2) - \frac{\eta s^2}{2} - c_e[E_m(s) - K] \quad (3)$$

Since the remanufacturer is the main carbon emitter, they invest in green technology to curb carbon emissions generated by production and inventory holding, the total emission amount in the system during each production cycle is given by

$$E_m(s) = (e_1 - b_1 s) \cdot D(s, p_1, p_2) + \frac{1}{2}(e_2 - b_2 s) \cdot D(s, p_1, p_2) \quad (4)$$

One has

$$\prod_M(s, w) = w(1-\theta) \cdot D(s, p_1, p_2) - c_m \cdot D(s, p_1, p_2) - \frac{h_m}{2} \cdot D(s, p_1, p_2) - \frac{h_b}{2} \cdot D(s, p_1, p_2) - \frac{\eta s^2}{2} - c_e[E_m(s) - K] \quad (5)$$

By using backward induction technology, we derive the equilibrium strategies of the remanufacturer, the retailer and the recycler.

Theorem 1. For the decentralized supply chain, the maximum profits per time unit of the retailer is $\pi_R(p_1)$ is concave in p_1 , and the corresponding optimal solution for retailer is

$$p_1^* = \frac{D_0 + \alpha s^* + \gamma p_2}{2\beta} + \frac{w^*}{2} + \frac{h_r}{4}$$

Theorem 2. For the decentralized supply chain, the maximum profits per time unit of the breaker is $\pi_B(l)$ is concave in l , and the corresponding optimal solution for recycler is

$$l^* = \sqrt{\frac{p_r + s_p}{s_0}}$$

Theorem 3. For the decentralized supply chain under VMI, the maximum profits per time unit of the remanufacturer is $\pi_M(s, w)$ is concave in s and w , and the corresponding optimal solutions for remanufacturer are

$$w^* = \frac{2\lambda_1\lambda_5 - \lambda_2\lambda_3}{\lambda_1\lambda_4 + \lambda_2^2} \quad \text{and} \quad s^* = \frac{\lambda_2\lambda_5 - 2\lambda_3\lambda_4}{\lambda_1\lambda_4 + \lambda_2^2}$$

3.3 Analysis of the centralized system

In the centralized system, the recycler, the remanufacturer and the retailer operate jointly as a single firm and determine the optimal selling price and the optimal sustainability level to maximize the total profit of the system. In this scenario, the total profit function can be formulated as

$$\prod_c(l, s, p_1) = \left\{ p_1 - \frac{h_r}{2} - \frac{p_r}{l} - \frac{s_c(l)}{l} - \frac{s_p \cdot (1-l)}{l} - c_m - \frac{h_m}{2} - \frac{h_b}{2} - c_e \left(e_1 - b_1 s + \frac{e_2 - b_2 s}{2} \right) \right\} \cdot D(s, p_1, p_2) - \frac{\eta s^2}{2} + c_e K \quad (6)$$

Theorem 4. For the centralized supply chain, the maximum total profits per time unit is Derived from Eq. (6), we can get

$$s^* = \frac{A_0}{A_1} - \frac{2\beta}{A_1} \cdot \frac{A_1 A_3 + 2A_0 A_4}{A_1^2 + 4\beta A_4} \quad \text{and} \quad p_1^* = \frac{A_1 A_3 + 2A_0 A_4}{A_1^2 + 4\beta A_4}$$

4. Numerical experiment

The preceding theory can be illustrated using the numerical example adopted from Xu et al. (2014). The corresponding parameters are $D_0 = 500$, $\alpha = 0.2$, $\beta = 0.8$, $\gamma = 0.4$, $e_1 = 50$, $b_1 = 0.45$, $e_2 = 23$, $b_2 = 0.34$, $c_e = 1$, $\eta = 25$, $K = 300$, $p_r = 5$, $p_2 = 800$, $\theta = 0.1$, $c_m = 8$, $h_m = 2$, $h_r = 3$, $h_b = 1$, $s_c = 1$ and $s_p = 0.3$. The computing results are summarized in Tables 1.

Table 1. The optimal solution for the numerical example

Model	The acceptance level l	Whole sale price w	Sustainability level s	Selling price p_l	Profit (Recycler, Remanufacturer, Retailer)	Profit of supply chain	Carbon emission $E_m(s)$
Decentralized system	0.58	649	33.76	781	(10,176, 157,670, 27,521)	217,765	15,976
Centralized system	0.71	NA	64.23	624	NA	259,410	15,707

Table 2. Sensitivity analysis of PPI (Decentralized)

Parameter	Base Column	% changed			
		-20%	-10%	+10%	+20%
D_0	500	-2.11	-1.04	1.01	2.01
α	0.2	-0.36	-0.18	0.18	0.35
β	0.8	-1.25	-0.61	0.58	1.13
γ	0.4	-0.68	-0.34	0.33	0.66
e_1	50	0.17	0.07	-0.06	-0.10
b_1	0.45	2.84	1.29	-1.10	-2.04
e_2	23	-1.22	-0.40	1.03	1.73
b_2	0.34	-2.11	-1.04	1.01	2.01
c_e	1	-0.82	-0.37	0.32	0.59
η	25	-0.24	-0.12	0.12	0.24
K	300	-0.05	0.02	0.02	0.05
p_r	5	-0.38	-0.19	0.18	0.37
p_2	800	-0.56	-0.28	0.26	0.52
θ	0.1	-0.32	-0.16	0.15	0.31
c_m	8	-0.32	-0.16	0.16	0.31
h_m	2	-0.11	-0.04	0.04	0.11
h_r	3	-0.06	-0.03	0.03	0.06
h_b	1	-0.86	-0.50	0.97	0.84
s_c	1	-0.11	-0.04	0.01	0.02
s_p	0.3	-0.36	-0.18	0.18	0.35

Table 3. Sensitivity analysis of PPI (Centralized)

Parameter	Base Column	% changed			
		-20%	-10%	+10%	+20%
D_0	500	-1.83	-0.90	0.88	1.74
α	0.2	-0.31	-0.16	0.15	0.30
β	0.8	-1.08	-0.53	0.50	0.98
γ	0.4	-0.59	-0.29	0.29	0.57
e_1	50	0.14	0.06	-0.05	-0.09
b_1	0.45	2.46	1.12	-0.95	-1.77
e_2	23	-0.79	-1.02	1.07	1.62
b_2	0.34	-1.83	-0.90	0.88	1.74
c_e	1	-0.71	-0.32	0.27	0.51
η	25	-0.21	-0.10	0.10	0.21
K	300	-0.04	0.02	0.02	0.04
p_r	5	-0.33	-0.16	0.16	0.32
p_2	800	-0.49	-0.24	0.23	0.45
θ	0.1	-0.28	-0.14	0.13	0.27
c_m	8	-0.28	-0.14	0.14	0.27
h_m	2	-0.11	-0.04	0.04	0.11
h_r	3	-0.06	-0.03	0.03	0.06
h_b	1	-0.86	-0.50	0.97	0.84
s_c	1	-0.11	-0.04	0.01	0.02
s_p	0.3	-0.31	-0.16	0.15	0.30

Note: PPI : percentage profit increasing = $(\pi_c^* - \pi_c^{*Default}) / \pi_c^{*Default}$.

5. Conclusion

This paper develops one-recycler, one-manufacturer and one-retailer low-carbon supply chain models for reused products. We incorporate two effective methods, carbon cap-and-trade regulation and investment in green technology, to curb carbon emissions. The remanufacturer's operational activities are the main sources of carbon emissions, and the remanufacturer invests in green technology to curb carbon emissions with the constraint of cap-and-trade regulation. Considering that the demand of retailer depends on the green technology level and the selling price of retailer, we formulate decentralized and centralized supply chain models respectively. Finally, we compare the profits and carbon emissions of decentralized and centralized models. As shown in Table 2 and Table 3, the value of PPI is most sensitive to parameters of market demand and the green technology effect in either model. This study contributes by: (i) developing closed-loop supply chain models with recycler-manufacturer-retailer interactions for reused products; (ii) incorporating both cap-and-trade regulation and green technology investment as emission-reduction mechanisms; (iii) modeling demand as dependent on price and technology level under decentralized and centralized structures; and (iv) providing comparative insights on profits, emissions, and sensitivity, with directions for multi-agent extensions. In the future, we may extend such one-remanufacturer and one-retailer supply chain to that with multiple remanufacturers and multiple retailers for vendor-managed product inventory.

Appendices

Appendix A. Proof of Theorem 1

As a Stackelberg game is considered in the decentralized system, we can use the backward sequential decision-making approach to analyze the problem. Firstly, substituting

$D(s, p_1, p_2) = D_0 + \alpha s - \beta p_1 + \gamma p_2$ into Eqs.(1), we have

$$\begin{aligned} \Pi_R(p_1) &= p_1(D_0 + \alpha s - \beta p_1 + \gamma p_2) - w(D_0 + \alpha s - \beta p_1 + \gamma p_2) - \frac{h_r}{2} \cdot (D_0 + \alpha s - \beta p_1 + \gamma p_2) \\ &= \left(p_1 - w - \frac{h_r}{2}\right) \cdot (D_0 + \alpha s - \beta p_1 + \gamma p_2) \end{aligned} \quad (A.1)$$

For any given wholesale price w and sustainability level s , we take the first partial derivative of $\Pi_R(p_1)$ with respect to p_1 , one has

$$\frac{\partial \Pi_R(p_1)}{\partial p_1} = \alpha s + \beta \left(\frac{h_r}{2} - 2p_1 + w\right) + D_0 + \gamma p_2 = 0 \quad (A.2)$$

We obtain the optimal price of remanufacturing item and the optimal price of all new item as

$$p_1^* = \frac{D_0 + \alpha s^* + \gamma p_2}{2\beta} + \frac{w^*}{2} + \frac{h_r}{4} \quad (A.3)$$

By taking the second partial derivative of $\Pi_R(p_1)$ with respect to p_1 , we have $\frac{\partial^2 \Pi_R(p_1)}{\partial p_1^2} = -2\beta < 0$, which implies that the profit of the retailer is a concave in the selling price p_1 .

Appendix B. Proof of Theorem 2

By substituting $D(s, p_1, p_2) = D_0 + \alpha s - \beta p_1 + \gamma p_2$ and $s_c = s_0 + \frac{l^2}{2}$ into Eqs.(2), we have

$$\Pi_B(l) = w\theta \cdot (D_0 + \alpha s - \beta p_1 + \gamma p_2) - \frac{p_r}{l} \cdot (D_0 + \alpha s - \beta p_1 + \gamma p_2) - \frac{s_0 \cdot l^2}{l} \cdot (D_0 + \alpha s - \beta p_1 + \gamma p_2) - \frac{s_p(1-l)}{l} \cdot (D_0 + \alpha s - \beta p_1 + \gamma p_2) \quad (B.1)$$

For any given wholesale price w and sustainability level s , we take the first partial derivative of $\Pi_B(l)$ with respect to l , one has

$$\frac{\partial \Pi_B(l)}{\partial l} = \frac{p_r}{l^2} - s_0 + \frac{s_p}{l^2} = 0 \quad (B.2)$$

We obtain the optimal acceptance level as

$$l^* = \sqrt{\frac{p_r + s_p}{s_0}} \quad (B.3)$$

By taking the second partial derivative of $\Pi_B(l)$ with respect to l , we have $\frac{\partial^2 \Pi_B(l)}{\partial l^2} = -2p_r - 2s_p < 0$, which implies that the profit of the Recycler is a concave in the acceptance level l .

Appendix C. Proof of Theorem 3

By substituting $p_1 = \frac{D_0 + \alpha s + \gamma p_2}{2\beta} + \frac{w}{2} + \frac{h_r}{4}$, $p_2 = \frac{D_0 + \alpha s + \gamma p_2}{2\beta} + \frac{w}{2} + \frac{h_r}{4}$ into Eqs.(5) we have

$$\Pi_M(s, w) = w(1-\theta) \cdot D(s, p_1, p_2) - c_m \cdot D(s, p_1, p_2) - \frac{h_m}{2} \cdot D(s, p_1, p_2) - \frac{h_b}{2} \cdot D(s, p_1, p_2) - \frac{\eta s^2}{2} - c_e [E_m(s) - K] \quad (C.1)$$

In addition, for calculating convenience, we define the following parameters:

$$\begin{aligned} \lambda_1 &= \frac{\alpha c_e}{2} \left(b_1 + \frac{b_2}{2} \right) - \frac{\eta}{2}, \\ \lambda_2 &= \frac{(1-\theta)\alpha}{2} - \frac{\beta c_e \left(b_1 + \frac{b_2}{2} \right)}{2}, \\ \lambda_3 &= c_e \left(b_1 + \frac{b_2}{2} \right) \left(\frac{D_0 - \gamma p_2}{2} - \frac{h_r \beta}{4} \right) - \frac{\alpha}{2} \left(c_m + \frac{h_m}{2} + \frac{h_b}{2} + c_e \left(e_1 + \frac{e_2}{2} \right) \right), \\ \lambda_4 &= \frac{(1-\theta)\beta}{2}, \\ \lambda_5 &= \frac{\beta}{2} \left(c_m + \frac{h_m}{2} + \frac{h_b}{2} + c_e \left(e_1 + \frac{e_2}{2} \right) \right) + (1-\theta) \left(\frac{D_0 - \gamma p_2}{2} - \frac{h_r \beta}{4} + \gamma p_2 \right) \text{ and} \\ \lambda_6 &= c_e K - \left\{ \left(c_m + \frac{h_m}{2} + \frac{h_b}{2} + c_e \left(e_1 + \frac{e_2}{2} \right) \right) \left(\frac{D_0 - \gamma p_2}{2} - \frac{h_r \beta}{4} + \gamma p_2 \right) \right\} \end{aligned}$$

One has

$$\Pi_M(s, w) = \lambda_1 s^2 + \lambda_2 s w + \lambda_3 s - \lambda_4 w^2 + \lambda_5 w + \lambda_6 \quad (C.2)$$

Taking the first partial derivative of $\Pi_M(s, w)$ with respect to s and w , we obtain the optimal sustainability level and wholesale price as

$$s^* = \frac{\lambda_2 \lambda_5 - 2\lambda_3 \lambda_4}{\lambda_1 \lambda_4 + \lambda_2^2} \quad (C.3)$$

$$w^* = \frac{2\lambda_1 \lambda_5 - \lambda_2 \lambda_3}{\lambda_1 \lambda_4 + \lambda_2^2} \quad (C.4)$$

Taking the second partial derivative of $\Pi_M(s, w)$ with respect to s and w , one has

$$\frac{\partial^2 \Pi_M(s, w)}{\partial s^2} = 2\lambda_1 \quad (C.5)$$

$$\frac{\partial^2 \Pi_M(s, w)}{\partial w^2} = -2\lambda_4 \quad (C.6)$$

$$\frac{\partial^2 \Pi_M(s, w)}{\partial s \partial w} = \lambda_2 \quad (C.7)$$

For the function to be concave, the following sufficient conditions must be satisfied:

$$\left(\frac{\partial^2 \Pi_M}{\partial s^2} \right) \left(\frac{\partial^2 \Pi_M}{\partial w^2} \right) - \left(\frac{\partial^2 \Pi_M}{\partial s \partial w} \right)^2 \geq 0 \quad (C.8)$$

and one or both

$$\frac{\partial^2 \Pi_M}{\partial s^2} \leq 0, \quad \frac{\partial^2 \Pi_M}{\partial w^2} \leq 0 \quad (C.9)$$

Substituting Eqs. (C.5), (C.6) and (C.7) into (C.8), one has

$$\left(\frac{\partial^2 \Pi_M}{\partial s^2} \right) \left(\frac{\partial^2 \Pi_M}{\partial w^2} \right) - \left(\frac{\partial^2 \Pi_M}{\partial s \partial w} \right)^2 = \left\{ \eta - c_e \alpha \left(b_1 + \frac{b_2}{2} \right) \right\} (1-\theta) \beta - \left[\frac{(1-\theta)\alpha}{2} - \frac{\beta c_e \left(b_1 + \frac{b_2}{2} \right)}{2} \right]^2$$

The necessary $\left(\frac{\partial^2 \Pi_M}{\partial s^2} \right) \left(\frac{\partial^2 \Pi_M}{\partial w^2} \right) - \left(\frac{\partial^2 \Pi_M}{\partial s \partial w} \right)^2 \geq 0$ condition for maximizing $\Pi_M(s, w)$ yields the lower bound of η :

$$\eta \geq \alpha c_e \left(b_1 + \frac{b_2}{2} \right) + \frac{1}{(1-\theta)\beta} \left[\frac{\alpha(1-\theta)}{2} - \frac{\beta c_e \left(b_1 + \frac{b_2}{2} \right)}{2} \right]^2 \quad (C.10)$$

Appendix D. Proof of Theorem 4

For calculating convenience, we define the following parameters:

$$B = \frac{h_R}{2} + \frac{p_r}{l} + \frac{s_c(l)}{l} + \frac{s_p(1-l)}{l} + c_m + \frac{h_m}{2} + \frac{h_b}{2l} + c_e e_1 + \frac{c_e e_2}{2} \quad \text{and}$$

$$C = c_e b_1 + \frac{c_e b_2}{2}.$$

$$\Pi_C = \Pi_A + \Pi_B + \Pi_C$$

$$= (p_1 - B + C \cdot s) \cdot (D_0 + \alpha s - \beta p_1 + \gamma p_2) - \frac{\eta s^2}{2} + c_e K$$

$$= p_1 D_0 - B D_0 + C D_0 s + \alpha p_1 s - \alpha B s + C \cdot s^2 - \beta p_1^2 + B \beta p_1 - C \beta p_1 s + p_1 \gamma p_2 - B \gamma p_2 + C \gamma p_2 s - \frac{\eta s^2}{2} + c_e K \quad (D.1)$$

$$\begin{aligned} \Pi_c = & (D_0 + \alpha s + B\beta + \gamma p_2)p_1 - (C \cdot \beta)p_1 s - \beta p_1^2 + (CD_0 - \alpha B + C\gamma p_2)s + \left(C - \frac{\eta}{2}\right)s^2 \\ & + (-BD_0 - B\gamma p_2 + c_e K) \end{aligned} \quad (D.2)$$

For further calculating convenience, we define the following parameters:

$$\begin{aligned} A_0 &= D_0 + \alpha s + B\beta + \gamma p_2, \\ A_1 &= C \cdot \beta, \quad A_2 = \beta, \quad A_3 = CD_0 - \alpha B + C\gamma p_2, \\ A_4 &= C - \frac{\eta}{2}, \quad \text{and} \quad A_5 = -BD_0 - B\gamma p_2 + c_e K. \end{aligned} \quad \text{One has}$$

$$\Pi_c = A_0 p_1 - A_1 p_1 s - A_2 p_1^2 + A_3 s + A_4 s^2 + A_5 \quad (D.3)$$

$$\frac{\partial \Pi_c(s, p_1)}{\partial p_1} = A_0 - A_1 s - 2\beta p_1 \quad (D.4)$$

$$\frac{\partial \Pi_c(s, p_1)}{\partial s} = -A_1 p_1 + A_3 + 2A_4 s \quad (D.5)$$

From $\frac{\partial \Pi_c(s, p_1)}{\partial p_1} = 0$ and $\frac{\partial \Pi_c(s, p_1)}{\partial s} = 0$, we obtain the optimal sustainability level and optimal selling price as

$$s^* = \frac{A_0}{A_1} - \frac{2\beta}{A_1} \cdot \left(\frac{A_1 A_3 + 2A_0 A_4}{A_1^2 + 4\beta A_4} \right) \quad (D.6)$$

And

$$p_1^* = \frac{A_1 A_3 + 2A_0 A_4}{A_1^2 + 4\beta A_4} \quad (D.7)$$

Taking the second partial derivative of $\Pi_c(s, p_1)$ with respect to s and p_1 , one has

$$\frac{\partial^2 \Pi_c(s, p_1)}{\partial s^2} = 2A_4 \quad (D.8)$$

$$\frac{\partial^2 \Pi_c(s, p_1)}{\partial p_1^2} = -2\beta \quad (D.9)$$

$$\frac{\partial^2 \Pi_c(s, p_1)}{\partial s \partial p_1} = -A_1 \quad (D.10)$$

For the function to be concave, the following sufficient conditions must be satisfied:

$$\left(\frac{\partial^2 \Pi_c}{\partial s^2} \right) \left(\frac{\partial^2 \Pi_c}{\partial p_1^2} \right) - \left(\frac{\partial^2 \Pi_c}{\partial s \partial p_1} \right)^2 \geq 0 \quad (D.11)$$

and one or both

$$\frac{\partial^2 \Pi_c}{\partial s^2} \leq 0 \quad \frac{\partial^2 \Pi_c}{\partial p_1^2} \leq 0 \quad (D.12)$$

Substituting Eqs. (D.7), (D.8) and (D.9) into (D.10), one has

$$\begin{aligned} & \left(\frac{\partial^2 \Pi_c}{\partial s^2} \right) \left(\frac{\partial^2 \Pi_c}{\partial p_1^2} \right) - \left(\frac{\partial^2 \Pi_c}{\partial s \partial p_1} \right)^2 \\ &= -4 \left[\left(c_e b_1 + \frac{c_e b_2}{2} \right) - \frac{\eta}{2} \right] \beta - \left[\left(c_e b_1 + \frac{c_e b_2}{2} \right) \beta \right]^2 \end{aligned} \quad (D.13)$$

The necessary condition $\left(\frac{\partial^2 \Pi_c}{\partial s^2} \right) \left(\frac{\partial^2 \Pi_c}{\partial p_1^2} \right) - \left(\frac{\partial^2 \Pi_c}{\partial s \partial p_1} \right)^2 \geq 0$ for maximizing $\Pi_c(s, p_1)$ yields the lower bound of η :

$$\eta \geq 2c_e \left(b_1 + \frac{b_2}{2} \right) + \frac{\beta c_e^2}{2} \left(b_1 + \frac{b_2}{2} \right)^2 \quad (D.14)$$

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