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Dual Collection Channels Under a Carbon Tax Scheme in CLSC: Decentralized vs. Alliance †

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Abstract: This paper compares dual collection mode strategies under carbon tax regulation: (1) a decentralized strategy when both manufacturer and retailer collect EoL independently and they determine their pricing and collection decision separately and (2) an alliance strategy by incorporating backward integration, when manufacturer and retailer make an alliance to recycle EoL but their pricing decisions are determined independently. The results show that the alliance strategy performs better in terms of total supply chain profit. Performing alliances benefits the manufacturer and supply chain.

Keywords: alliance strategy; carbon tax; closed-loop supply chain; dual collection channels

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1. Introduction

Recycling and remanufacturing have gained a lot of attention from academia and industries due to their ability to tackle some issues, including core availability, the environment, and economics. Thus, the recycling strategy becomes critical. To recycle EoL products, we have to collect EoL. The collection of EoL can be performed by one or more actor(s) in the supply chain, such as a manufacturer, supplier, retailer, or third party. The literature review papers regarding closed-loop supply chains [1,2] also mentioned the importance of recycling and remanufacturing in closed-loop supply chains. In this paper, we focus on the dual recycling channels strategy where a manufacturer and a retailer can collect EoL simultaneously. Under dual recycling channels, the decision-making process could be achieved in a decentralized or cooperative manner. In this study, we explore vertical integration or alliance as a cooperation strategy. This concept is widely adopted in the real world. For example, for 3C products (computer, communication, and consumer electronics), Apple collaborates with its retailers to collect their EoL. Another example of this mechanism is also adopted in the electric vehicle battery industry, where leading manufacturers, such as Honda and Toyota, are forming alliances with their dealers or retailers to collect used batteries [3]. According to reference [3], alliances in recycling can improve supply chain performance effectively.

In response to environmental issues, many countries and regions adopt stringent regulations to reduce carbon emissions. The regulations are created by the government to attract both individuals and industries to participate in reducing greenhouse gas emissions. In fact, different countries have different policies to reduce carbon emissions, such as carbon tax and carbon cap and trade [4]. According to the World Bank (2024), the number of carbon taxes and emissions trading schemes in operation worldwide is now 75, of which 39 adopt carbon taxes. For example, the Netherlands and France are the top two countries that have higher carbon taxes in 2024 [5]. This is what motivated us to use carbon tax as a policy to reduce emissions. Our study differs from previous studies in several ways as mentioned in Table 1.

Table 1. Research gap.

Paper	Supply Chain		Dual Recycling Channel	Product Recycling and Remanufacturing	Coordination	Carbon Emission
	Forward	Reverse				
[3]	√	√	√	√	Alliance and Contract	
[6]		√	√		Contract	
[7]	√	√	√	√	Centralized	
[8]	√	√	√	√	Centralized	
[9]	√	√		√	Contract	Carbon tax
[10]	√	√	√	√		Technology investment
[11]	√	√		√	Alliance	
[12]	√	√			Alliance	
[13]	√	√			Alliance	
[14]	√	√		√	Alliance	
[15]	√	√	√		Centralized	
[16]	√	√		√		Carbon tax
[17]	√	√		√	Centralized	Cap and trade
This paper	√	√	√	√	Alliance	Carbon tax

Firstly, this paper differs from most of the dual recycling channel research streams that have been studied by references [3,6–8,11,13]. In the context of dual recycling channels, our paper strongly relates to reference [3]; however, this paper considers the environmental impact of implementing a carbon tax, while reference [3] did not consider it. Ref. [6] only consider reverse channels rather than closed-loop supply chains. Ref. [7] examines dual recycling channels composed of a retailer and a third party within a closed-loop supply chain by focusing on the competitive interactions in decentralized and centralized settings. Ref. [8] explores joint third parties with multiple (re)manufacturers and retailers in a closed-loop supply chain structure. Ref. [9] studies dual forward and reverse channels by comparing decentralized and centralized strategies. Ref. [10] explores dual-channel closed-loop supply chains by considering the environmental impact of technology investment. All in all, this paper differs from those papers above in terms of the supply chain structure and environmental impact considerations, specifically carbon tax. The second research stream is coordination under alliance strategy by doing vertical integration that has been explored by references [11–14]. Another research stream is related to carbon tax in remanufacturing. Carbon tax has been widely used to reduce the environmental impact of remanufacturing in previous studies. This has been reviewed by [18]. However, most of the previous studies only consider a single recycling channel, including [15–17].

However, the topic of dual recycling strategies considering carbon emissions, especially using carbon tax policy, particularly considering both non-cooperative and cooperative aspects, has still not been extensively explored. Thus, this study aims to fill this gap by investigating whether decentralized or alliance is more beneficial for dual recycling closed-loop supply chains under carbon tax regulation and analyzing the impact of some different variables on the supply chain benefit.

2. Problem Description and Method

This study considers a closed-loop supply chain with a manufacturer and a retailer, which engages in both forward selling and reverse collection and recycling activities. The manufacturer produces a product and sells it to the customer through a retailer in a forward supply chain. Then, both a manufacturer and a retailer collect EoL products from customers in the reverse supply chain.

The game theory approach is utilized to see the dynamics of each player within the supply chain. To obtain the equilibrium solutions of each strategy, we use backward induction. The detail of the notations is described in Table 2. This paper considers non-cooperation (called strategy D) and cooperation in recycling activities by forming an alliance between manufacturers and retailers (called strategy A).

Table 2. Notations.

Parameter	Description
α	Initial demand
β	Consumer price sensitivity
D	Demand
K	Scaling parameter of the recycling cost
η	Relative recycling cost efficiency
e_n	Unit carbon emissions for producing each unit of new product
e_r	Unit carbon emissions for producing each unit of remanufactured product
e_{cm}	Unit carbon emissions for collecting each unit to the manufacturer
e_{cr}	Unit carbon emissions for collecting each unit to the retailer
c_m	Unit cost of new product
c_r	Unit cost of remanufactured product
t	Unit transfer payment from manufacturer to retailer
b_m	Unit transfer payment from manufacturer to customer
b_r	Unit transfer payment from retailer to customer
c_e	The rate of carbon tax levied by the government
π_m	Manufacturer's profit
π_r	Retailer's profit
Decision variable	
w	Unit wholesale price
p	Unit retailer price
τ_m	Collection rate of the manufacturer
τ_r	Collection rate of the retailer

Without loss of generalization, several relevant assumptions are established: Assumption 1. Unit production cost for a new product is greater than unit production cost of a remanufactured product, $c_m > c_r > 0$. Assumption 2. Wholesale price per unit is cheaper than retail price per unit, $p > w > 0$. Assumption 3. Unit carbon emissions for producing a new product are larger than unit carbon emissions for producing a remanufactured product, $e_n > e_r$. Assumption 4. In the EoL collection activity, manufacturer collection consumes more carbon emissions than retailer collection, $e_{cm} > e_{rm}$. Assumption 5. The total collection rate from the manufacturer and retailer is less than one, $0 \leq \tau_m + \tau_r \leq 1$. All products returned from customers to both the manufacturer and retailer can be successfully remanufactured by the manufacturer. Then, the total collection cost for the manufacturer and retailer is represented as $C(\tau_m) = K{\tau_m}^2 + b_m \tau_m D$ and $C(\tau_r) = \eta K{\tau_r}^2 + b_r \tau_r D$, respectively, in which the first component is fixed collection cost or investment cost in collection and the second component is variable collection cost [19].

This study adopts a linear demand function [19], $D(p) = \alpha - \beta p$. The carbon tax mechanism is adopted to calculate the carbon emissions cost. The total carbon emission cost (CC) is the government carbon tax rate (c_e) multiplied by the sum of the emissions in the production of a new product $[D(e_n(1-\tau_m-\tau_r))]$, remanufacturing $[D(e_r(\tau_m+\tau_r))]$, and collection activities $[D(e_{cm}\tau_m + e_{rm}\tau_r)]$. Thus, the total carbon emissions cost is $CC = c_e D((e_n(1-\tau_m-\tau_r)) + (e_r(\tau_m+\tau_r)) + (e_{cm}\tau_m + e_{rm}\tau_r))$.

2.1. Decentralized Strategy (Strategy D)

Decentralized CLSC is when both manufacturer and retailer collect EoL and make decisions independently. First, the manufacturer determines the wholesale price (w) and collection rate (τ_m), then the retailer decides the retailer price (p) and collection rate (τ_r). To solve the problem, the backward induction is adopted in this model. The decision sequence in strategy D is as follows:

$$\max_{w,\tau_m} \pi_m \rightarrow \max_{p,\tau_r} \pi_r. \tag{1}$$

The manufacturer's profit function is as follows:

$$\max_{w,\tau_m} \pi_m = [w - c_m(1 - \tau_m - \tau_r) - c_r(\tau_m + \tau_r)]D - C(\tau_m) - t\tau_r D - CC. \tag{2}$$

The first term represents the wholesale revenue and benefits of remanufacturing, the second term denotes the total manufacturer's collection cost, the third term is the transfer payment cost from manufacturer to the retailer, and the last term is the total carbon emissions cost.

$$\max_{p,\tau_r} \pi_r = (p - w)D + (t - b_r)\tau_r D - \eta K {\tau_r}^2. \tag{3}$$

The retailer wants to maximize the profit. In Equation (3), the first component is the profit by selling products in forward channel, the second component is the benefit of collection, and the last component is the investment cost in the recycling activity.

2.2. Alliance Strategy (Strategy A)

Under this strategy, the manufacturer and retailer cooperate when determining the collection rate (τ_m, τ_r). While pricing decisions are determined individually. As both the manufacturer and retailer collaborate when making decisions in collection activity, the transfer price will be treated as an internal cost, thus it has no impact on CLSC. So, the first alliance determines the recycling rate simultaneously (τ_m, τ_r). Then, the manufacturer decides the wholesale price (w), and the last retailer determines the retailer price (p). The decision sequence is as follows:

$$\max_{\tau_m,\tau_r} \pi_A \rightarrow \max_{w} \pi_m \rightarrow \max_{p} \pi_r. \tag{4}$$

The optimization problems for the manufacturer and retailer, respectively, are as follows:

$$\max_{w} \pi_m = [w - c_m(1 - \tau_m - \tau_r) - c_r(\tau_m + \tau_r)]D - K{\tau_m}^2 - CC, \tag{5}$$

$$\max_{p} \pi_r = (p - w)D - \eta K{\tau_r}^2. \tag{6}$$

The alliance profit function can be determined by summing the manufacturer's profit function and the retailer's profit function.

$$\max_{\tau_m,\tau_r} \pi_A = \max_{w} \pi_m + \max_{p} \pi_r. \tag{7}$$

3. Results

Backward induction is utilized to solve the Stackelberg game. The step-by-step to obtain equilibrium solutions for each strategy is explained in the subsection below:

3.1. Problem Solving Strategy D

First, we solve stage 2, where the retailer decides the retailer's price and the retailer's collection rate. Given the manufacturer's decisions $(w,\ \tau_m)$, D is substituted into Equation (3), then ensure that π_r is jointly concave in variable p and τ_r. By solving $\frac{\partial \pi_r}{\partial p} = 0$ and $\frac{\partial \pi_r}{\partial \tau_r} = 0$ simultaneously, we can find the retailer price and retailer collection rate are, respectively,

$$p = \frac{(b_r - t)^2 \alpha\beta - 2K(\alpha + w\beta)\eta}{\beta\Big((b_r - t)^2\beta - 4K\eta\Big)}, \tag{8}$$

$$\tau_r = \frac{(b_r - t)(\alpha - w\beta)}{(b_r - t)^2\beta - 4K\eta}. \tag{9}$$

Next, in stage 1, the manufacturer decides the wholesale price and its collection rate. Then, D, $C(\tau_m)$, and CC are substituted into Equation (2) and put into Equations (8) and (9) to Equation (2). Thus, we obtain the complete Equation (2). From that equation, we can verify that π_m is jointly concave in w and τ_m. Next, the manufacturer's best response can be obtained by solving the first-order condition of π_m with respect to w and τ_m simultaneously to obtain

$$w = \frac{A_2}{\beta B_1}, \tag{10}$$

$$\tau_m = \frac{(A_1)(\alpha - (c_m + c_e e_n)\beta)\eta}{B_1}, \tag{11}$$

where

$$A_1 = (b_m - c_m + c_r + c_e(e_{cm} - e_n + e_r));\ A_2 = ((b_r - t)\beta((b_r - 2c_m + 2(c_r + c_e(-e_n + e_r + e_{rm})) + \mathrm{t})\alpha + \\ (c_m + c_e e_n)(b_r - t)\beta) + (A_1)^2\alpha\beta - 4K(\alpha + (c_m + c_e e_n)\beta))\eta);\ A_3 = \alpha - (c_m + c_e e_n)\beta;\ B_1 = 2(b_r - c_m + \\ c_r + c_e(-e_n + e_r + e_{rm}))(b_r - t)\beta - 8K\eta + (b_m - c_m + c_r + c_e(e_{cm} - e_n + e_r))^2\beta\eta.$$

3.2. Problem Solving Strategy A

In stage 3, the retailer determines the retail price. Given the parameters (w, τ_m, τ_r), we can substitute D into Equation (6) and take the second derivatives of π_r to confirm that π_r is concave in terms of p. Therefore, we can find p by applying the first-order condition of π_r with respect to p.

$$p = \frac{\alpha + w\beta}{2\beta}. \tag{12}$$

In stage 2, the manufacturer determines the wholesale price. By substituting D and CC into Equation (5) and then incorporating Equation (12) into the revised Equation (5), we derive the updated version of Equation (5). From this equation, we can confirm that the profit function π_m is concave in relation to w. The manufacturer's optimal response can be determined by solving the first-order condition of π_m with respect to w.

$$w = \frac{\alpha + \beta(-c_m(-1 + \tau_m + \tau_r) + c_r(\tau_m + \tau_r) + c_e((e_{cm} + e_r)\tau_m + (e_r + e_{rm})\tau_r - e_n(-1 + \tau_m + \tau_r)))}{2\beta}. \tag{13}$$

While in stage 1, the alliance decides the collection rate for the manufacturer and retailer simultaneously. Substituting p and w into Equation (7) and taking the first-order condition of π_A with respect to τ_m and τ_r simultaneously to obtain

$$\tau_m = \frac{3A_4(-A_3)\eta}{B_2}, \tag{14}$$

$$\tau_r = \frac{3(c_m - c_r + c_e(e_n - e_r - e_{rm}))(-A_3)}{B_2}, \tag{15}$$

where $A_4 = (c_m - c_r - c_e(e_{cm} - e_n + e_r))$; $B_2 = B_3 + (-16\mathrm{K} + B_3)\eta$; $B_3 = 3(-c_m + c_r + c_e(-e_n + e_r + e_{rm}))^2\beta$.

3.3. Equilibrium Solutions

The equilibrium solutions of strategy D are as follows:

$$w^* = \frac{A_2}{\beta B_1}, \tag{16}$$

$$\tau_m{}^* = \frac{(A_1)A_3\eta}{B_1}, \tag{17}$$

$$p^* = \frac{1}{\beta\left((b_r - t)^2\beta - 4\mathrm{K}\eta\right)}\left((b_r - t)^2\alpha\beta - 2\mathrm{K}\eta\left(\alpha + \frac{A_2}{B_1}\right)\right), \tag{18}$$

$$\tau_r{}^* = \frac{(b_r - t)(A_3\beta)}{B_1}, \tag{19}$$

$$\pi_m{}^* = -\frac{\mathrm{K}(A_3)^2\eta}{\beta B_1}, \tag{20}$$

$$\pi_r{}^* = \frac{\mathrm{K}(A_3)^2\eta\left(-(b_r - t)^2\beta + 4\mathrm{K}\eta\right)}{\beta(B_1)^2}. \tag{21}$$

The equilibrium solutions of strategy A are as follows:

$$w^* = \frac{B_3\alpha + 3(-A_4)^2\alpha\beta\eta - 8\mathrm{k}(\alpha + A_5)\,\eta)}{\beta B_2}, \tag{22}$$

$$\tau_m{}^* = \frac{3(A_4)(-A_3)\eta}{B_2}, \tag{23}$$

$$p^* = \frac{B_3\alpha + 3(-A_4)^2\alpha\beta\eta - 4\mathrm{K}(3\alpha + (A_5)\eta)}{\beta B_2}, \tag{24}$$

$$\tau_r{}^* = \frac{3(c_m - c_r + A_6)(-\alpha + A_5)}{B_2}, \tag{25}$$

$$\pi_m{}^* = \frac{\mathrm{K}(\alpha - A_5)^2\left(32\mathrm{cl} - 9(-c_m + c_r + c_e(e_{cm} - e_n + e_r))^2\beta\right)\eta^2}{\beta(B_2)^2}, \tag{26}$$

$$\pi_r{}^* = \frac{\mathrm{K}(\alpha - A_5)^2\eta\left(-9(-c_m + c_r - A_6)^2\beta + 16\mathrm{K}\eta\right)}{\beta(B_2)^2}, \tag{27}$$

where $A_5 = (c_m + c_e e_n)\beta$; $A_6 = c_e(e_n - e_r - e_{rm})$.

4. Discussions

To make further analysis, we use numerical analysis with these specific parameter values in Mathematica. All the parameter values are as follows: $\alpha = 100, \beta = 1.9, c_m = 20, c_r = 10, t = 0.0792, \mathrm{K} = 8000, \eta = 0.0828, e_{cm} = 1.5, e_{rm} = 0.5, e_n = 4, e_r = 2, c_e = 0.5, b_r = 1.2, b_m = 2, \mathrm{t} = 1.7$. The optimum solutions for those two strategies are shown in Table 3 below:

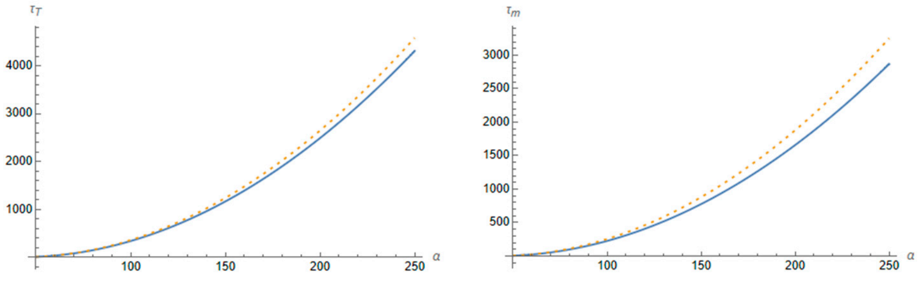
Table 3. The equilibrium solutions for strategy D and strategy A.

Equilibrium	Strategy D	Strategy A
w^*	37.2347	36.2189
p^*	44.9318	44.4253
${\tau_m}^*$	0.0075	0.0149
${\tau_r}^*$	0.0055	0.1898
${\pi_m}^*$	224.065	254.11
${\pi_r}^*$	112.625	104.096
${\pi_T}^*$	336.69	358.206
CE^*	58.3423	57.8127

According to the numerical experiment, performing Alliance benefits the manufacturer and supply chain in terms of profit. The manufacturer's and supply chain's profit in strategy A is greater than in strategy D, while the retailer does not benefit from an alliance because the retailer's profit under strategy A is less than her profit under strategy D. In terms of collection rate, strategy A yields more returned products both to the manufacturer and retailer. While considering the wholesaler and retailer prices, strategy A charges a lower price than strategy D. As strategy A obtains a higher collection rate than strategy D, thus the total carbon emission strategy A is lower than strategy D. It makes sense because the fewer the number of returned products, the newer the product produced. In fact, the carbon emissions for producing a new product are higher than for a remanufactured product. However, if global regulation regarding environmental impact is stringent, performing recycling and remanufacturing only might not be enough. As recycling and remanufacturing depend on the collection rate. Thus, applying some strategy that influences the collection rate and carbon emission, such as technology investment in low carbon emission, might be promising in the near future.

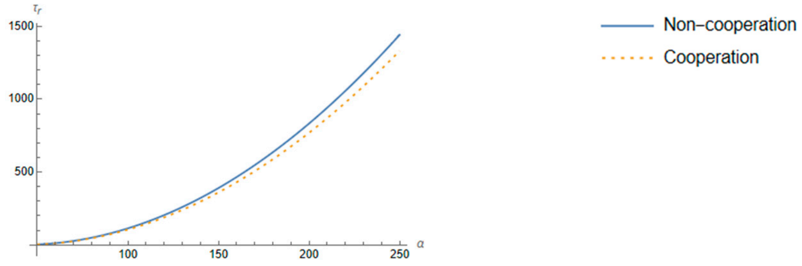
For the long-term period, these conditions might hurt the retailer due to the opportunity loss to make higher profits. Thus, it would be advantageous for the manufacturer to come up with a strategy that can bring both parties into a win-win situation, such as a cost-sharing or revenue-sharing contract. By implementing cost-sharing contracts, the manufacturer will share an amount of collection cost with the retailer, or through a revenue-sharing mechanism, the manufacturer will share an amount of revenue earned from recycling activities. Thus, the retailer also feels benefited from this collaboration.

Figure 1 describes the effect of changing α on the supply chain, manufacturer, and retailer profit. When α is low, the supply chain, manufacturer, and retailer profit in strategy A and strategy N are indifferent. When $100 \leq \alpha \leq 250$, the supply chain profit and manufacturer profit in strategy A are better than in strategy D, while retailer profit in strategy D is better than in strategy A. Higher α leads to a higher gap in the total supply chain; that is because the gap in the collection rate also rises significantly.



(**a**) (**b**)

Figure 1. *Cont.*



(**c**)

Figure 1. The effect of α. (**a**) The effect of ∝ on the total profit. (**b**) The effect of ∝ on the manufacturer's profit. (**c**) The effect of ∝ on the retailer's profit.

5. Conclusions

This study discusses a dual recycling strategy considering carbon tax to achieve the maximum profit. Non-cooperation and cooperation strategies are compared to determine which strategy benefits the supply chain and/or each member. We divide our contributions into two parts. First, in the context of knowledge, this paper has filled the gap in the dual recycling channels research domain by forming an alliance between the manufacturer and retailer as a cooperative strategy and considering the environmental impact, and carbon emissions, as important measures along with profitability. According to the numerical analysis, the following conclusions are drawn: An alliance strategy benefits the supply chain and manufacturer in terms of profit. While the retailer is in a loose situation if performing Alliance. By cooperating, the total collection rate is higher and total carbon emissions are lower than with non-cooperation. However, performing analytical analysis in the future is essential to provide robust solutions. Another direction, developing other collaboration mechanisms, will also give more insights for both players.

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