Influence of Market Efficiency and Energy Saving/ Emission Reduction on Closed-loop Supply Chain

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Abstract
This study addresses the problem of inequality between social and corporate benefits in creating a recyclable low-carbon supply chain under the "dual carbon" policy. Our research constructs a two-level closed-loop supply chain in which manufacturers lead, retailers follow, and demand is influenced by consumers' preference for corporate emissions reduction behavior and market efficiency. This study explores the effects of consumer preference for emission reduction, firm's cost of emission reduction, market efficiency sensitivity, and market efficiency input cost on the pricing by using the Stackelberg game model and input strategies of manufacturers and retailers under centralized and decentralized decision making respectively. The results show that in a closed-loop supply chain that considers market efficiency and energy efficiency, the overall profitability of the centralized decision-making system is greater than that of decentralized decision-making.

Keywords: *closed-loop supply chain, carbon emission reduction, market efficiency, consumer preference*

1. Introduction

Nowadays, with the increasing problems of global resource shortage and environmental degradation, "double carbon" has become an important issue that has attracted the attention of countries around the world. People's quality of life and purchasing capacity are gradually been improved with rapid economic development. At the same time, the rate of product upgrading is accelerating due to improvements in corporate productivity, which raises an important issue: the disposal of used and waste products. For example, it is supposed that waste products can be disposed of properly and recyclable resources put into use. In that case, the utilization rate of resources can be significantly improved, energy-saving and emission reduction can be effectively achieved, and an environmentally friendly and sustainable economy can be developed.

2. Theoretical Lenses

Ferguson et al. Ferguson et al. (2006) addressed the problem of whether those manufacturers should recover the value of their end-of-life products for reuse through remanufacturing by proposing a model to support manufacturers' recovery strategies when they encounter competitive threats in the market of remanufactured products [1]. Mahmoudi et al. (2014) proposed a data planning model to minimize the total cost (including reverse logistics and remanufacturing) of a multi-layered, multi-product reverse supply chain for the cost optimization problem. However, in a carbon-sensitive market, reducing carbon emissions results in higher production costs and stimulates an increase in reverse demand [2]. Du et al. (2015) proposed a new carbon-sensitive demand function for the seemingly contradictory objectives of abatement costs and profit-seeking and introduced a carbon-sensitive cost function to capture the deviation in production costs due to carbon abatement [3]. Shi et al. (2015) proposed a remanufacturing model with multiple reverse channels of retailer recycling, third-party recycling, and manufacturer recycling based on a recycling responsibility-sharing approach for product recycling responsibility in a closed-loop remanufacturing supply chain consisting of manufacturers, third-party logistics service providers, and retailers [4]. Taleizadeh et al. (2017) studied joint pricing and refund optimization under non-cooperative and cooperative strategies in a two-level supply chain [5]. Ata Allah et al. (2018) investigated the impact of imposing marketing efforts on manufacturers' and retailers' optimal decisions and profits in a two-

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channel closed-loop supply chain system [6]. Ran et al. (2021) used Stackelberg's game correlation theory to investigate the differences between channel impacts from three perspectives: closed-loop supply chains, dual-channel supply chains, and government intervention, in order to address the issue of resource waste and carbon emissions [7]. Zhang et al. (2021) developed a dynamic Stackelberg game model based on finite rational expectations for supply disruptions in a closed-loop supply chain system with multiple participants and analyzed the game's evolution [8].

3. Research Questions and Hypothesis Development

3.1. Question Description

This paper focuses on optimal decision-making and profit-sharing in a two-stage closed-loop supply chain consisting of a single manufacturer and a single retailer. In a closed-loop supply chain where both market efficiency and consumer preferences influence market demand, the manufacturer takes the lead in advertising and carbon reduction, and the retailer is responsible for sales and recycling, the combined effect of market efficiency and energy reduction on the overall supply chain. The symbols set out in this paper are shown in Table 1 below.

Table 1 Conforms to the definition

Symbols	Meaning	Symbols	Meaning
p_1	Phase I Retail Price	θ	Recycling price
p_2	Phase II Retail Price	D	Potential market demand
q_1	Phase I requirements	s_r	Consumer Sensitivity Factor for Corporate Emissions Reduction Behavior, $0<s_r<1$
q_2	Phase II requirements	β	Consumer preference factor for remanufactured products, $0<\beta<1$
w_1	Phase I Wholesale Prices	c_r	Emission reduction cost factor, $0<c_r<1$
w_2	Phase II Wholesale Prices	a	Market effectiveness input efforts
q_{2r}	Phase II remanufactured product requirements	c_a	market effectiveness unit input cost factor, $0<c_a<1$
q_{2n}	New product requirements for phase II	s_a	Sensitivity factor of consumers to the market effectiveness behavior of companies, $0<Sa<1$
r	Corporate emissions reduction input efforts		

In the first phase, the manufacturer promotes the launch of the product. a indicates the manufacturer's efforts to invest in advertising, marketing, etc. on market effectiveness. C_a is the market effectiveness input cost factor. S_a is the sensitivity of consumers to advertising or other marketing techniques placed by the manufacturer. In the production process, the manufacturer achieves an abatement rate r through means like technological innovation to reduce emissions. At the same time, the corresponding abatement effort generates an abatement cost factor of C_r. Since there is a green consumer preference for firms' emissions reduction behavior, there is a sensitivity factor of s_r corresponding to firms' emissions reduction efforts that affect the number of market purchases. Larger values of C_a and C_r indicate higher market effectiveness and abatement costs for the same input. Larger values of S_a and S_r indicate the greater ability of the same market effectiveness and abatement input to influence increased consumer demand for the product.

Under the combined effect of firms' market effectiveness and consumers' preferences for emission reductions, the quantity of the product demanded in the first Phase q_1 is:

$$q_1 = D - p_1 + s_r * r + s_a * a \qquad (1)$$

Following Ata Allah et al. (2018) in the model, the abatement cost function C(r) is set in this paper as:

$$C(r) = \frac{c_r * r^2}{2} \qquad (2)$$

Based on Ata Allah et al. (2018) in the model, this paper sets the market effectiveness input cost function C(a) as:

$$C(a) = \frac{c_a * a^2}{2} \qquad (3)$$

The manufacturer produces new products at a wholesale price w_1 to the retailer who sells the products to consumers at a retail price q_1. When consumers have finished using the products, they produce used products, which are recycled by the retailer at a set recycling price θ.

In the second stage, the manufacturer produces a new product alongside the remanufactured product and sells it to the retailer at the wholesale price of w_2 in the second stage. The retailer then sells the product to the market at the new product price p_{2n} and the remanufactured product price p_{2r}. Drawing on the research setup of Ferguson et al. [1] (2006), the number of new versus remanufactured products produced in the second stage is influenced by consumer preference for remanufactured products β. The new product and the remanufactured product have an abatement input effort of r due to the influence of consumers' preference for the firm's abatement behavior Sr and their preference for the remanufactured product β. Therefore, the demand function q_{2r} for the new product in the second stage is:

$$q_{2n} = D - p_{2n} - \beta * p_{2r} + s_r * r \quad (4)$$

In the second phase, the remanufactured product inverse demand function q_{2r} is:

$$q_{2r} = D - \frac{p_{2r}}{\beta} - p_{2n} \quad (5)$$

The model uses a Stackelberg game with the manufacturer as the dominant player and the retailer as the follower. However, given that there may be both centralized and decentralized decision-making between the manufacturer and the retailer during the game, the model will be developed in later sections of this paper under both decision-making approaches.

3.2. Formulation of Hypotheses

The following hypotheses are formulated in this paper to better explain the model as well as to facilitate the study.

H1: Manufacturers advertise product launches and invest in market effectiveness in the first phase, but the investment in market effectiveness can have the same impact on product demand in both phases.

H2: It is assumed that the potential market demand for the product is the same for both phases, i.e.

$$q_1 = q_2 \quad (6)$$

And the second stage demand is the sum of the new and remanufactured products, i.e.

$$q_2 = q_{2n} + q_{2r} \quad (7)$$

H3: Remanufactured products are already green products and are not affected by corporate emissions reduction practices.

H4: According to Ferguson et al [1] (2006), two considerations arise as consumers purchase remanufactured products: 1. They are concerned about the quality of the remanufactured product. 2. The production cost of remanufactured products is lower than that of new products due to "fair price". Based on these two considerations, consumers have a lower willingness to pay for remanufactured products. Therefore, the range of the consumer preference coefficient β for remanufactured products is.

$$0 < \beta < 1 \quad (8)$$

If β = 0, it means that consumers are not willing to buy remanufactured products. If β = 1, it means that consumers have the same willingness to buy remanufactured products as new products.

H5: In order to simplify the calculations, the manufacturer's manufacturing costs, the retailer's selling costs, and the remanufacturing costs are not considered. The study assumes that these three costs are zero.

4. Closed-loop supply chain model with centralized decision-making

4.1. Modeling

Centralized decision-making aims to investigate manufacturers and retailers as a community, belonging to the same company, using a uniform pricing strategy to get the optimal system profit. In this segment, the main objectives identified are optimal product pricing, market effectiveness input effort, and energy efficiency input effort. The profit equation for a two-stage closed-loop supply chain under centralized decision-making is as follows.

$$\pi_{sc} = \pi_1 + \pi_2 = \left\{p_1 * q_1 - \frac{c_r}{2} * r^2 - \frac{c_a}{2} * a^2\right\} + \left\{p_{2n} * q_{2n} - \frac{c_r}{2} r^2 + (p_{2r} - \theta) * q_{2r}\right\} \quad (9)$$

The system profit is the sum of the producer's and manufacturer's Phase 1 and Phase 2 profits. In the first stage, the manufacturer advertises the product launch. Inputs are made in the production process to reduce emissions, generating market effectiveness inputs and energy saving and emission reduction input costs. The product is then sold to the consumer at a price of p_1. In the second phase, retailers recycle and remanufacture used products at the recycling price θ and then sell the remanufactured products at p_{2r}. At the same time, the manufacturer continues to produce new products, which are sold at a price of p_{2n}. In the second phase of new product production, the manufacturer still needs to invest in abatement, where abatement costs are incurred.

4.2. Model analysis

This model needs to be solved to obtain the optimal pricing strategy. The optimal solution for the first stage is first obtained by considering the dynamic decision of the system. The second-order derivatives of p_1, r_1 and a for the first stage of the supply chain are expressed using the Hessian matrix for π_1.

Theorem 1: In the centralized decision-making model, the system profit in the first phase should satisfy: $-2c_a c_r + c_r {s_a}^2 + c_a {s_r}^2 < 0$, and there is a unique optimal solution（p_1^*, r_1^*, a^*）。

Bringing p_1^*, r_1^*, a^* into Equation (9) leads to maximizing system profit π_1 in the first phase of centralized decision making.

For the second phase, the optimal solutions p_1^* and r_1^* found in the first phase are brought into the second phase model using the second-order derivatives for p_{2n}, p_{2r}, and θ. The Hessian Matrix is used for the calculation of π_2.

Theorem 2: In the centralized decision model, there is a unique optimal solution（p_{2n}^*，p_{2r}^*，θ^*）。

Bringing p_{2n}^*, p_{2r}^*, and θ^*, into Equation (91) leads to maximizing system profit π_2 under the second stage of centralized decision making.

The following corollary is proposed under the centralized decision model by using the method of deriving and comparing optimal solutions,

Corollary 1: The first order derivative of C_a is calculated based on the resulting optimal decision yields to obtain $\frac{\partial p_1}{\partial c_a} < 0$, $\frac{\partial p_{2n}}{\partial c_a} < 0$, $\frac{\partial p_{2r}}{\partial c_a} > 0$, $\frac{\partial \theta}{\partial c_a} < 0$. Research has shown that under centralized decision-making. If the cost of market efficiency inputs is higher, the supply chain will set lower selling. Furthermore, recycling prices for new products and manufacturers and retailers will be more willing to increase the price of remanufactured products to make more profit by investing less in market efficiency.

Corollary 2: The first order derivative of C_r is calculated based on the resulting optimal decision to obtain $\frac{\partial p_1}{\partial c_r} < 0$, $\frac{\partial p_{2n}}{\partial c_r} < 0$, $\frac{\partial p_{2r}}{\partial c_r} > 0$, $\frac{\partial \theta}{\partial c_r} > 0$. The study shows that the selling price of new products is negatively correlated with the abatement cost factor in the concentration model. The price of remanufactured products and recycling is positively related to the abatement cost coefficient. The production of new products involves energy-saving and emission reduction. If an increase in the cost of emission reduction means higher production costs for new products, manufacturers and retailers will increase the price of recycled and remanufactured products.

Corollary 3: The first order derivative of S_a is calculated based on the resulting optimal decision yields to obtain $\frac{\partial p_1}{\partial s_a} > 0$, $\frac{\partial p_{2n}}{\partial s_a} > 0$, $\frac{\partial p_{2r}}{\partial s_a} < 0$, $\frac{\partial \theta}{\partial s_a} < 0$. If consumers are more sensitive to market effectiveness tools such as corporate advertising and brand image, companies can raise the price of new products to maximize benefits.

Corollary 4: By comparing the optimal solutions, the order of centralized decision pricing strategies should be $p_1 > p_{2n} > p_{2r} > \theta$. Due to the problem of conflicting supply and demand for goods, the sales of a new product in the second stage will be hindered if its retail price is the same as the retail price in the first stage. Therefore, the second stage retail price should be lower than the first stage sales price in order to obtain the optimal profit. And the recycling price should be lower than the sales price of the remanufactured product so as to ensure the profitability of the remanufactured product sales.

5. Closed-loop supply chain model with decentralized decision-making

5.1. Modeling

In a decentralized decision-making model, the manufacturer and the retailer no longer make decisions, but each side aims to maximize its interests. In the Stackelberg game model, the manufacturer is the dominant player, and the retailer is the follower. The retailer is responsible for recycling and remanufacturing the used product and earning a profit from the sale of the remanufactured product. Manufacturers decide on market effectiveness inputs, energy efficiency inputs, and wholesale prices by first considering retailers' profitability to maximize their interests. Under decentralized decision-making, the manufacturer's two-stage closed-loop supply chain profit equation is.

$$\pi_m = \pi_{m1} + \pi_{m2} = \{w_1 q_1 - \frac{c_r}{2} r^2 - \frac{c_a}{2} a^2\} + \{w_2 q_{2n} - \frac{c_r}{2} r^2\} \quad (10)$$

The retailer profit equation is,

$$\pi_r = \pi_{r1} + \pi_{r2} = \{(p_1 - w_1) q_1\} + \{p_{2r} q_{2r} + (p_{2n} - w_2) q_{2n} - \theta q_{2r}\} \quad (11)$$

In the decentralized decision-making model, in the first phase, the manufacturer advertises the product launch. Inputs are made to the production process to reduce emissions, which generates market effectiveness inputs and energy saving and emission reduction input costs. The product is then wholesaled to retailers at a wholesale price of w_1. The retailer sets the retail price p_1 to sell to the consumer based on the manufacturer's wholesale price w_1. In the second stage, the manufacturer continues to produce new products for wholesale to the retailer at wholesale price w_2. The retailer recycles and remanufactures the used product at a recycling price θ and then sells the remanufactured product at a price of p_{2r}.

At the same time, a retail price p_{2n} is set for sales based on the manufacturer's second stage wholesale price w_2. In the second stage of new product production, the manufacturer still needs to invest in abatement.

5.2. Model analysis

As the decision-making is decentralized between the two supply chain members, the manufacturer will determine the market efficiency input level, the energy-saving input level, and the wholesale price in the first phase, and then the retailer will decide the retail price based on the manufacturer's pricing strategy. Manufacturers develop their own pricing strategies by first considering the impact of their pricing strategies on retailers. While maximizing their own interests, they avoid conflicts of interest with retailers. Therefore, the solution to the model should take the reverse reasoning approach, where the manufacturer's two-stage profit function π_{m1}, π_{m2} is the response function to the retailer's decision.

Theorem 3: In the first phase of the decentralized decision model, there exists a unique optimal solution (w_1^*, r^*, a^*) when $\frac{1}{4}[c_a(s_r^2 - 4c_r) + c_r s_a^2] < 0$, is satisfied.

Theorem 4: Under the second phase of decentralized decision making, when $0.5 < \beta < 1$ is satisfied, there exists a unique optimal manufacturer wholesale price w_2^*:

$$w_2^* = \frac{d\{c_r s_a^2(-1+\beta) + c_a[-4c_r(-1+\beta) + 2s_r^2\beta]\}}{(8c_a c_r - 2c_r s_a^2 - 2c_a s_r^2)(1+\beta)} \quad (12)$$

Meanwhile, in the second phase, retailers generate optimal new product retail price, remanufactured product price (p_{2n}, p_{2r}) and recycling price θ.

$$p_{2n} = \frac{d\{-c_r s_a^2(3+\beta) + 2c_a[s_r^2\beta + 2c_r(3+\beta)]\}}{(16c_a c_r - 4c_r s_a^2 - 4c_a s_r^2)(1+\beta)} \quad (13)$$

$$p_{2r} = \frac{d\{-c_r s_a^2(3+\beta) + 2c_a[-s_r^2(2+\beta) + 2c_r(3+\beta)]\}}{(16c_a c_r - 4c_r s_a^2 - 4c_a s_r^2)(1+\beta)} \quad (14)$$

$$\theta = \frac{d\{-2c_a[-s_r^2(-2+\beta) + 6c_r(-1+\beta)] + 3c_r s_a^2(-1+\beta)\}}{16c_a c_r - 4c_r s_a^2 - 4c_a s_r^2} \quad (15)$$

Based on the derivation and comparison of the optimal solutions of the decentralized decision model and the comparison with the results of the centralized decision model, the following inferences are made.

Theorem 5: The first order derivative of C_a based on the optimal decision from the dispersion model gives $\frac{\partial w_1}{\partial c_a} < 0$, $\frac{\partial w_2}{\partial c_a} < 0$, $\frac{\partial p_1}{\partial c_a} < 0$, $\frac{\partial p_{2n}}{\partial c_a} < 0$, $\frac{\partial p_{2r}}{\partial c_a} > 0$, $\frac{\partial \theta}{\partial c_a} > 0$. It shows that in the dispersion model, the market effectiveness cost coefficient is negatively correlated with the wholesale and retail price of new products and positively correlated with the price of remanufactured products and recycling prices. Unlike centralized decision making, it is assumed that since the manufacturer is responsible for input into market effectiveness. With higher promotional costs, manufacturers will reduce their promotional inputs, which may lead to a decrease in the number of new products in demand. The retailer will therefore increase revenue by increasing the price of recycling to get consumers to sell more used products to the retailer, and then by increasing the price of remanufactured products.

Theorem 6: Taking the first order derivative of Sa from the optimal decision obtained from the dispersion model yields, the following can be obtained: $\frac{\partial w_1}{\partial s_a} > 0$, $\frac{\partial w_2}{\partial s_a} > 0$, $\frac{\partial p_1}{\partial s_a} > 0$, $\frac{\partial p_{2n}}{\partial s_a} > 0$, $\frac{\partial p_{2r}}{\partial s_a} < 0$, and $\frac{\partial \theta}{\partial s_a} < 0$. In the dispersion model, consumer sensitivity to advertising is positively related to manufacturers' and retailers' pricing of new product, and negatively related to the price of remanufactured products and recycling. If consumers are sensitive to advertising and promotion of the product, companies will raise the price of the new product to increase revenue.

Theorem 7: By comparing the calculation of market effectiveness inputs, energy-saving, and emission reduction inputs, and overall profit in the centralized and decentralized models, we can obtain $a_c > a_d$, $r_c > r_d$, $\pi_c > \pi_d$. Manufacturers in the centralized model need to invest more effort in market effectiveness and energy efficiency than that in the decentralized model. At the same time, the overall profitability under the combined impact of both is greater.

6. Conclusion

This paper establishes a two-level closed-loop supply chain in which manufacturers lead, retailers follow, and consumer preferences influence demand for firms' abatement behavior and market effectiveness. The study discusses how manufacturers and retailers develop pricing and input strategies in response to consumer preferences for abatement, abatement costs, market effectiveness sensitivity, and market effectiveness input costs under centralized and decentralized decision making, respectively. The study found through model derivation, decision comparison, and numerical analysis that profit levels, emission reductions, and market efficiency input levels behaved differently under the different decision models. Moreover, these factors have different effects on the pricing strategies of the two models. Companies can make their own optimal decisions by varying the different parameters to suit the reality of the situation. The study found that (1) in an environment influenced by market efficiency and energy efficiency, supply chain companies using centralized decision-making are a better decision-making model than decentralized decision-making. (2) The sensitivity of consumer advertising and corporate image of emission reduction is negatively correlated with the price of remanufactured products. The higher the sensitivity, the lower the price of remanufactured products. (3) Consumer environmental preferences are positively correlated with overall supply chain profits. Higher consumer preferences for corporate emissions reduction behavior lead to higher profits in closed-loop supply chains, whether the decision is centralized or decentralized. (4) Regardless of the decision model, the cost coefficient for market effectiveness input effort is negatively correlated with the wholesale and retail price of new products and positively correlated with the price of remanufactured products and recycling. (5) In the decentralized decision-making model, as manufacturers and retailers pursue their respective interests to maximize, manufacturers consider their efforts to reconcile the inputs and benefits of market effectiveness and emissions reduction, resulting in reduced operational efficiency. (6) The coefficient of consumer sensitivity to market efficacy and the coefficient of firm sensitivity to abatement behavior have a more significant impact on the decision to centralize the model. (7) In a market environment where consumer market effectiveness is sensitive, manufacturers and retailers in a decentralized decision-making model will adopt strategies to increase sales prices to suit the market environment.

This paper makes the following recommendations for companies in closed-loop supply chains influenced by market effectiveness and energy efficiency.

The future development of manufacturers and retailers should be holistic, with centralized decision-making to maximize the value generated in the production and distribution process and redistribution of profits through profit-sharing mechanisms.

Before the product is launched and promoted, sufficient research needs to be done to understand the market environment and how consumers will react to the promotion of the product and the investment in emission reduction. Companies can increase wholesale and retail prices to expand revenues in an environment of high market efficiency sensitivity and environmental awareness. At the same time, it is also essential to anticipate the market efficiency and cost of emission reduction. In the case of high costs, companies may be able to reconcile revenues and costs by increasing the price of remanufactured products and recycling prices.

Companies actively guide consumers to green consumption concepts and create an excellent environment-friendly image. For example, when promoting their products, companies not only promote the sales of their products, but they can also guide consumers in the process of shaping environmental awareness, which has a positive impact on the sales of both new and remanufactured products.

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