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Research article

Strategic pricing and coordination in a closed-loop supply chain under cap-and-trade regulation: a quality improvement perspective

Fuli Zhou[1,*], Yueli Li[1], Bo Yu[1], Shouqin Zhou[2], Saurabh Pratap[3], Amir Karbassi Yazdi[4] and Gonzalo Valdés González[4]

[1] College of Economics and Management, Zhengzhou University of Light Industry, Zhengzhou, China
[2] School of Mechanical Engineering and Mechanics, Xiangtan University, Xiangtan, China
[3] Department of Mechanical Engineering, Indian Institute of Technology (IIT BHU), Varanasi, India
[4] Departamento de Ingeniería Industrial y de Sistemas, Facultad de Ingeniería, Universidad de Tarapacá, Arica, Chile

* **Correspondence:** Email: deepbreath329@outlook.com.

Abstract: Under the cap-and-trade regulation (CATR), remanufacturing is regarded as an effective approach for the low-carbon transformation of production methods. However, the quality of remanufactured products is frequently subject to skepticism. Although quality improvement can enhance market competitiveness, it inevitably leads to higher costs. Given this, we attempted to investigate the coordination mechanism of a closed-loop supply chain (CLSC) under the CATR, taking quality improvement into account. The centralized and decentralized models were constructed to analyze the specific impact of product quality improvement on the decision-making of CLSC members. In addition, to motivate manufacturers to improve product quality, we introduced a revenue sharing contract (RSC) between retailers and manufacturers to help achieve coordination. It was found that the degree of quality upgrading decreases as the cost coefficient of quality improvement investment rises. Under these circumstances, product demand declines even when prices are lowered. The numerical study demonstrates that the designed RSC is effective to help realizing the coordination of the CLSC.

Keywords: quality improvement; carbon cap-and-trade regulation (CATR); closed-loop supply chain (CLSC); revenue sharing contract (RSC); stackelberg game theory
Mathematics Subject Classification: Primary: 90B06

1. Introduction

With increasing manufacturing production and soaring consumption, greenhouse gas emissions are rising rapidly, which brings great threats to human beings and the sustainable development of society. In response to the current plight of global warming, it has become a consensus to reduce carbon emissions and achieve circular economic development. Although more than 50 countries around the world have announced the peak of carbon emissions [1], it is difficult to ensure the achievement of the goal by relying exclusively on the market mechanism. Global greenhouse gas emissions continue to persist at elevated levels, which requires the government to effectively control carbon emissions and achieve sustainable development goals through policy guidance [2]. The CATR, due to their flexibility grounded in market mechanisms, are regarded as significant policy instruments for advancing the development of a low-carbon economy [3] and fostering a low-carbon transformation of industrial structures [4,5]. The CATR allows enterprises to freely trade emission rights within the prescribed carbon emission quotas. Corporations exceeding their carbon emission quotas are required to pay higher costs, whereas those with surplus carbon quotas can sell them to reduce their emission reduction expense. The CATR compels enterprises to seek low-carbon approaches and enhance resource allocation efficiency through regulatory and market-based measures. Specifically, the policy effectively integrates carbon emissions into the operational costs, which not only mitigates carbon emissions but also transforms corporate profit models, so as to foster dual improvement of environmental and economic benefits [6].

Although the CATR can achieve carbon reduction targets, carbon emissions are still high in some industries, such as manufacturing. Manufacturing, as the primary sector for material production, is recognized as a major source of environmental pollution, but it is also the key entry point to promote the circular economy by realizing resource recovery and green transformation under the current trend of green transformation [7]. The CATR stimulates enterprises to achieve carbon emission reduction through recycling and remanufacturing. Remanufacturing is to restore the performance of waste products through repair and upgrading, and then enter them back into the market cycle. This approach reduces greenhouse gas emissions by extending the product life cycle and reducing dependence on original materials in the production process. Hence, under the target of cutting carbon emissions, remanufacturing is recognized as an efficacious approach for the collection of waste resources and low-carbon transformation of production methods [8]. The research demonstrates that remanufacturing can not only take full advantage of the added value of discarded products but also achieve carbon emission reduction while ensuring product quality, which shows that there is consistency between low-carbon transformation and product quality improvement [9]. In practice, many high-value products, such as automotive engines, have been manufactured in the CLSC [10]. To establish an environmentally friendly brand image, manufacturers are glad to advertise the sustainable practices associated with their products to consumers [11]. However, consumers are beginning to doubt the quality of products made from reusable materials [12], and product quality is important for consumers who have exacting standards for products and are glad to pay high prices for them [13]. Therefore, in the face of the changing demands of consumers, enterprises need to improve product quality while mitigating carbon emissions.

Product quality improvement is the process of enhancing product competitiveness by improving product performance attributes and the augmentation of their added value. Quality improvement is often accompanied by an increase in costs. Especially under the CATR, companies are required to pay for carbon dioxide emissions, which undoubtedly increases the cost pressure in the remanufacturing process. Obviously, carbon trading policies and quality improvement will have a direct impact on manufacturers' costs, while quality improvement will also affect consumer demand, both of which will have an impact on the CLSC. Therefore, in the CLSC, it is of considerable practical significance to examine how quality improvement affects supply chain pricing under the CATR. The previous literature mainly analyzed the influence of various influencing factors on CLSC pricing and quality decision-making in the supply chain operation process. For example, Taleizadeh et al. [14] discussed the effect of different return methods on CLSC pricing, profit, carbon emission reduction, and quality improvement under the CATR. Chen et al. [15] explored how manufacturers' efforts in green quality improvement affect decisions. However, these studies assume that the quality upgrading degree of products is the same, ignoring the impact of the difference in the quality upgrading degree of new and remanufactured products on the decision-making of the CLSC.

Due to the discrepancy of raw materials between new products and remanufactured products, the quality upgrading degree of remanufactured products is lower. The difference in quality upgrading degree makes the decision-making of the CLSC more complicated. Retailers may be resistant to remanufactured products because of a lower degree of quality upgrading, while manufacturers may choose to raise wholesale prices in response to balance the extra expenditure caused by quality improvement and the implementation of the CATR. Majumder et al. [16] and Özcan et al. [17] believed that when CLSC members focus primarily on their marginal benefits while neglecting the overall interests, a "double marginalization effect" arises. Therefore, appropriate mechanisms are essential to regulate the behavior of supply chain members, thereby ensuring that their efforts are aligned with the goal of maximizing collective interests and achieving supply chain coordination. In view of this, under the CATR, the CLSC coordination research considering product quality improvement principally solves the following problems.

(1) What are the optimal decisions under both decentralized and centralized models considering quality improvement under the CATR?

(2) How do the cost coefficient of quality improvement investment and carbon trading price influence optimal decisions?

(3) How to coordinate the participants' interests among CLSC members by designing a contact mechanism under this innovative scenario?

The innovations of this paper are highlighted as follows. First, the existing studies have typically examined the effects of the CATR or product quality improvement on CLSC decisions separately. However, the combined impact of these two factors on pricing, demand, and profit decisions of CLSC members is systematically analyzed in this study. Second, prior studies frequently assume that the quality upgrading degrees of new and remanufactured products are identical. In contrast, this study focuses on the differential characteristics of quality upgrading degrees between these two product types. Finally, given the limited existing research on coordination mechanisms for the CLSC that consider quality improvement, a suitable coordination contract will be designed to address this research gap.

The primary contributions of this study are outlined below. First, decentralized and centralized decision-making models are constructed to systematically investigate the CLSC decision, taking into account product quality improvement under the CATR. Second, to effectively enhance the manufacturer's motivation for quality improvement, a revenue-sharing contract is introduced, providing an actionable solution to incentivize manufacturers to actively invest in quality improvement. Finally, through numerical simulation, the dual effects of carbon trading price and the cost coefficient of quality improvement investment on CLSC pricing strategies and member profits are explored in depth. The effectiveness of the coordination contract is verified, demonstrating that the revenue sharing contract (RSC) can successfully achieve coordinated optimization of the CLSC.

We will now present the paper structure. Section 2 introduces the literature overview that is consistent with this article. The problem statement and research hypotheses are presented in Section 3. Subsequently, Section 4 constructs a decentralized model, a centralized model, and a coordination contract. Section 5 presents the results of numerical simulations conducted for the purpose of analyzing the models. Section 6 introduces managerial insights. Finally, a summary of the conclusions is given in Section 7.

2. Literature review

2.1. Closed-loop supply chain (CLSC) management

To pursue the efficient utilization of resources and achieve sustainable development, product recycling and remanufacturing are being actively promoted by countries and enterprises. The CLSC is precisely in response to this call, forming a closed-loop and sustainable resource utilization model through the close links of various stages including design, production, consumption, recycling, and reuse, which not only guarantees economic benefits but also realizes lower carbon emissions. Thus, the CLSC is a key strategy to achieve environmental protection and promote the realization of the circular economy.

Since its introduction by Guide and Van Wassenhove [18], the CLSC has quickly gained widespread attention as a management approach that integrates forward and reverse logistics. The existing research analyzes the production pricing decision-making problems of new and remanufactured products, and discusses the influence of various factors on the economic, social, and environmental benefits of the CLSC. Zou et al. [19] analyzed the influence of authorized remanufacturing and outsourced remanufacturing on pricing decisions, social welfare, and the environment. Raz and Souza [20] revealed that manufacturers' recycling of waste products can increase the profits of the CLSC through constructing four different recycling models. Zheng et al. [21] studied how retailers' concerns about fairness affect CLSC members' pricing decisions and earnings distribution. Wu [22] believed that the government's taxation or subsidy policies can alleviate the intensity of price competition. Yao et al. [23] examined the repercussions of consumers' heightened environmental consciousness on CLSC member strategies. Huang and Wang [24] discussed the impact of manufacturer's encroachment, in that original equipment manufacturer (OEM) sets up direct sales channels and forms a competitive relationship with retailers, and retailer's information sharing behavior on the CLSC decision. They revealed that information sharing and encroachment behavior are consistently beneficial to manufacturers, whereas these factors will be advantageous for retailers only when certain conditions are met. Song et al. [25] found that manufacturers' altruistic behavior helps to enhance the profitability of the CLSC. In addition, scholars have begun to integrate environmental factors into supply chain management and have researched the impact of carbon policy constraints on pricing strategies and carbon emission reduction. Huang et al. [26] concluded that the CATR is more incentive to reduce carbon emissions in a weak market environment than the carbon tax policy under a competitive CLSC. It has been found by Chen et al. [27] that the implementation of the CATR leads to a reduction in carbon emissions, but it also causes a decrease in consumer surplus.

When studying the optimal decision of the electric vehicle CLSC, Tsao and Ai [28] concluded that the implementation of the CATR not only reduces carbon emissions without increasing return rates but also enables green suppliers to achieve higher profits with the assistance of government subsidies, ultimately leading to a decrease in product prices.

Existing research has analyzed the CLSC decision-making problems under the circumstances of government regulation policy constraints, different recycling channels, different supply chain power structures, different remanufacturing strategies, and the limited rationality of decision makers. With the deepening of research, the impact of environmental factors on the CLSC has also been considered. However, existing research has often overlooked consumers' demand for product quality, thus ignoring the influence of quality improvement on CLSC decision-making.

2.2. Quality improvement

As an effective way to enhance the independent innovation ability and market competitiveness, product quality improvement is very important in supply chain operations. Therefore, more and more scholars investigate the effect of improving product quality on the pricing strategies of the CLSC. The study was initially conducted with a focus on improving the quality of new products. Jia et al. [29] conducted an analysis to assess the profit of both a sales model and a leasing model taking into account product quality improvement. They found that intertemporal purchase behavior and price penalty strategies make sales more profitable than leasing. De Giovanni and Zaccour [30] formulated a two-period model based on manufacturers' investment in improving product quality, discovering that it is essential for manufacturers to update their pricing strategies according to the degree of product quality upgrading when consumers passively return old products. Wang et al. [9] discussed the effect of quality improvement and low-carbon emissions on enterprise decisions and concluded that product quality improvement has a greater influence on enterprise profits. The impact of online reviews on the quality improvement of two competing manufacturers was examined by Huang et al. [31] amid the growth of e-commerce. It was found that high-quality firms tend to increase their degree of quality upgrading in response to differences in online reviews between the two products, whereas low-quality firms tend to decrease their degree of quality upgrading.

The market for remanufactured products is gradually expanding under the current low-carbon and sustainable development context, but the quality of these products remains the key factor affecting consumer purchase intentions. Consequently, research has been conducted to improve the quality of remanufactured products. It was found by Li et al. [32] that when the investment cost for quality upgrading is relatively low, enterprises are more likely to shorten production cycles through remanufacturing to secure short-term profits, rather than investing additional resources to improve the iterative quality of remanufactured products. This ultimately weakens the incentive for quality upgrading. Feng et al. [33] revealed that a greater degree of quality upgrading in refurbished products hinders both the enhancement of remanufactured product quality and the expansion of production scale. Ma et al. [34] revealed that product quality improvement significantly enhances the production efficiency of enterprises by constructing a three-layer joint optimization nonlinear mixed-integer decision model. Furthermore, this model can coordinate the conflict between remanufacturing outsourcing and product optimization and improvement, enabling stakeholders to maximize their profits. As research progressed, scholars began to consider the influence of environmental factors on CLSC decisions. Mao et al. [35] pointed out that the CATR can encourage manufacturers to improve product quality and expand production. Xu et al. [36] indicated that government subsidies for manufacturers' carbon emissions significantly increase consumers' willingness to purchase remanufactured products. This increased willingness, in turn, further drives improvements in the quality of remanufactured products.

Although the above researches consider manufacturers' product quality improvement on CLSC pricing decisions, it fails to fully evaluate the effect of quality improvement under the CATR. With the deepening of research, some scholars began to consider the influence of product quality improvement on CLSC decision-making under the CATR. However, these studies assume that the quality upgrading degree of products is the same, disregarding the impact of the difference in the quality upgrading degree of new and remanufactured products on CLSC decision-making.

2.3. Coordination mechanism

After considering the behavior of independent decision-makers, it is still necessary to start from the entire supply chain to pursue the maximization of the overall interests of the CLSC, achieving supply chain coordination. This emphasizes that the goal of each enterprise is consistent with the overall goal so that the entire supply chain can achieve superior performance [37]. However, supply chain coordination is usually difficult to accomplish autonomously. Savku and Weber [38] posited that supply chain participants tend to either overreact or underreact to information and events based on the overall market sentiment. In order to realize supply chain coordination, it is essential to utilize some coordination mechanisms, which are usually presented in the form of contracts to motivate each decision-maker to consider the overall interests [39].

Many researchers have explored the relevant contract mechanism. It has been demonstrated by Qiao et al. [40] that both quantity discount contracts and cost-sharing contracts can effectively coordinate the CLSC. Specifically, the quantity discount contracts have shown superior performance in profit-maximization scenarios, primarily because cost-sharing contracts are limited to aligning the interests of manufacturers and retailers, whereas quantity discount contracts can balance the profits among suppliers, manufacturers, and retailers simultaneously. However, when the focus shifts to carbon emission reduction, cost-sharing contracts offer greater advantages. Wan et al. [41] revealed that when investments in information-sharing platforms resulted in diminished profits for CLSC participants, the revenue-sharing and cost-sharing contract could incentivize these participants to adopt such platforms and maximize their profits. As consumer requirements for product quality escalate, research has been initiated by scholars into the design of coordination contracts between manufacturers and retailers to induce them to carry out quality improvement efforts. Chakraborty et al. [13] discussed the effect of three distinct coordination contracts on decisions, revealing that cost-sharing contracts can make the CLSC generate a greater degree of quality upgrading and higher profits. Fan et al. [42] analyzed the effect of expected quality improvement responsibility cost sharing on decisions of different channel leadership structures. They found that irrespective of the channel leadership structure, the contract combining quantity discount and quality improvement cost sharing can coordinate the CLSC, improving its efficiency.

The above are studies of CLSC contract coordination. However, most of the above literatures ignore the consumer's requirements for product quality, so the significance of integrating quality improvement considerations into operational decision-making is overlooked in the CLSC. Although Chakraborty and Fan have considered the effect of quality improvement on the CLSC, their analysis does not emphasize the difference in the degree of quality upgrading of new products and remanufactured products. Furthermore, the influence of the CATR has been overlooked in the CLSC. The literature closely related to this study is summarized in Table 1 as follows.

Table 1. Primary relative literature.

Relative Literature	CATR	Quality improvement		Coordination mechanism	Differences in the degree of quality upgrading
		New product	Remanufactured product		
Chakraborty et al. [13]		✓	✓	✓	
Taleizadeh et al. [14]	✓	✓	✓		
Fan et al. [42]		✓	✓	✓	
Feng et al. [33]		✓	✓		
Cheng and Wang. [5]		✓	✓		
Mao et al. [35]	✓	✓	✓		
Xu et al. [36]	✓	✓	✓		
Ma et al. [34]		✓	✓		
This study.	✓	✓	✓	✓	✓

3. Model description

3.1. Problem description

The operational process of the model is presented in Figure 1. In the game process, the manufacturer serves as a leader in formulating the strategic planning of the entire supply chain. Meanwhile, the retailer, as a supply chain follower, flexibly adjusts sales and inventory strategies according to the strategic orientation provided by manufacturers. With intensifying competition, the manufacturer improves product quality through technological innovation and optimization of production processes to further expand market share. Considering the lack of consumers' cognition of remanufactured products, the expected value of new products and remanufactured products is different. Therefore, they will be clearly labeled and priced differently at the point of sale. In addition, the government allocates manufacturers a specified number of gratuitous carbon emission quotas in order to encourage them to reduce greenhouse gas emissions. If the quantity of carbon emissions generated during the production process exceeds the amount of free quotas granted by the government, the manufacturer is required to purchase excessive parts. Conversely, any surplus allowances may be sold on the carbon trading market to generate revenue.

3.2. Assumptions and notations

This section presents a series of hypotheses, aiming to provide a clear theoretical framework for the construction of the model. At the same time, while maintaining the fundamental nature of the research, we decided to appropriately simplify some relatively minor conditions to enhance the focus on the core issues of the research.

Assumption 1. Remanufactured products will have obvious logos, making it easy for consumers to distinguish between new and remanufactured products. Therefore, differential pricing strategies are implemented for the two product categories [43].

Assumption 2. The recycling of waste products is limited due to imperfect recycling channels and a dearth of environmental awareness among consumers. Concurrently, a considerable proportion of consumers have insufficient knowledge of remanufactured products, accompanied by concerns about their performance. This causes a smaller market demand for remanufactured products, so $Q_n > Q_r > 0$.

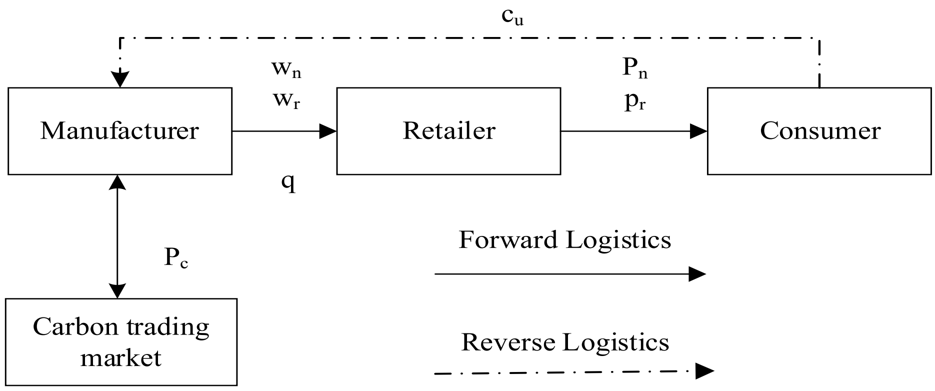

Figure 1. Framework of the model.

Assumption 3. To ensure that manufacturers are motivated to remanufacture the product, it is necessary to meet $c_n > c_r + c_u$. In addition, the production of remanufactured products uses a large number of original parts, reducing the steps involved in the mining and processing of raw materials. Consequently, the carbon emissions generated by remanufactured products are lower, that is, $e_n > e_r > 0$ [44].

Assumption 4. The raw materials employed for new products differ from those utilized for remanufactured products in production. Consequently, despite undergoing identical quality improvement procedures, the quality of the remanufactured product cannot be guaranteed to attain an exact parity with that of new products. Accordingly, we introduce the concept of a remanufactured product quality improvement discount coefficient, denoted as l, and lq represents the degree of quality upgrading for remanufactured products. In addition, we set the quality improvement investment as a one-time cost, amounting to kq^2, where$k$ is the quality improvement investment cost coefficient. When k is large, the amount of money needed for product quality improvement is greater, and the efficiency is lower [14].

Assumption 5. To guarantee that the remanufactured products are able to satisfy the market demand, we assume that there are sufficient quantities of waste products on the market. The quality of the new and remanufactured products is improved by manufacturers for the first time.

Assumption 6. Drawing on existing research, the demand for new and remanufactured products is modeled based on consumer utility. The total utility perceived by consumers from both product types is $U = \sum_{i=n,r} Q_i D_i - \frac{1}{2}\sum_{i=n,r} D_i^2 - \theta D_n D_r + qD_n + lqD_r - \sum_{i=n,r} p_i D_i$ [45,46]. Specifically, the term $\sum_{i=n,r} Q_i D_i$ captures the increase in utility with rising demand, while the term $-\frac{1}{2}\sum_{i=n,r} D_i^2$ reflects the concept of consumption saturation. The term $-\theta D_n D_r$ indicates product substitutability, with the higher substitution degree θ leading to a reduction in total utility. The term $qD_n + lqD_n$ represents the utility gain associated with quality improvement. The core characteristic of $-\sum_{i=n,r} p_i D_i$ is that perceived utility decreases as product price increases. By solving in accordance with the principle of consumer utility maximization, the market demand for new products is derived as $D_n = \frac{lq\theta + \theta Q_r - \theta p_r - q - Q_n + p_n}{\theta^2 - 1}$, and that for remanufactured products as $D_r = \frac{lq - \theta Q_n - \theta q + \theta p_n + Q_r - p_r}{1 - \theta^2}$.

The related variables and parameters are presented in Table 2.

Table 2. Definition of related variables and parameters.

Variables/Parameters	Definition
Decision variables	
q	Degree of quality upgrading
ω_n、ω_r	Unit wholesale price of new/remanufactured products
p_n、p_r	Unit retail price of new/remanufactured products
Parameters	
Q_n、Q_r	Initial market size of new/remanufactured products
D_n、D_r	Market demand for new/remanufactured products
c_n、c_r	Unit production cost of new/remanufactured products
c_u	Unit waste recycling cost
e_n、e_r	Historical emission intensity per unit of new/remanufactured products
E	Free carbon emissions allocated to manufacturers
$\theta (0 < \theta < 1)$	Substitution degree of new and remanufactured products
U	Consumer utility
p_c	Unit carbon trading price
π_M、π_R、π_C	Profit of manufacturer/retailer/supply chain system
k	The cost coefficient of the quality improvement investment
l	Remanufactured product quality improvement discount coefficient

4. Model formulation and results analysis

4.1. The decentralized model (Model D)

In Model D, the retailer is relatively independent, in that the manufacturer does not directly control the downstream retailer. Manufacturers, as the leader, first determine the degree of quality upgrading q and the wholesale price under the CATR. Retailers are not regulated by the CATR, as the followers, and then determine product sales prices in consideration of manufacturers' decisions. Therefore, the expressions of profit are as follows under Model D:

$$\pi_M^D = (\omega_n - c_n)D_n + (\omega_r - c_r - c_u)D_r - p_c[(e_n D_n + e_r D_r) - E] - kq^2 \quad (1)$$

$$\pi_R^D = (p_n - \omega_n)D_n + (p_r - \omega_r)D_r \quad (2)$$

According to the principle of reverse reasoning, the optimal solutions can be obtained when $k > \frac{l^2 - 2\theta l + 1}{8(1-\theta^2)}$, as follows:

$$p_n^* = \frac{8Ak\theta^2 + ((-5e_n p_c - 3Q_n - 5c_n)l - 3B)\theta + Al^2 + 3Bl - 8Ak + 4e_n p_c + 4c_n}{32k\theta^2 + 4l^2 - 8l\theta - 32k + 4} \tag{3}$$

$$p_r^* = \frac{(-3D\theta+4B+4Q_r)l^2-((-5B+2Q_r)\theta+3D)l+(8k\theta^2-8k-1)(B+4Q_r)}{32k\theta^2+4l^2-8l\theta-32k+4} \tag{4}$$

$$\omega_n^* = \frac{8Ck\theta^2 + ((-3e_n p_c - Q_n - 3c_n)l - B)\theta + Cl^2 + Bl - 8Ck + 2e_n p_c + 2c_n}{16k\theta^2 + 2l^2 - 4l\theta - 16k + 2} \tag{5}$$

$$\omega_r^* = \frac{(-D\theta+2B+2Q_r)l^2+(-3B\theta+D)l+(8k\theta^2-8k-1)(B+2Q_r)}{16k\theta^2+2l^2-4l\theta-16k+2} \tag{6}$$

$$D_n^* = \frac{(-8B\theta+8D)k+(-Dl+B)l}{32k\theta^2+4l^2-8l\theta-32k+4} \tag{7}$$

$$D_r^* = \frac{(-8D\theta+8B)k+Dl-B}{32k\theta^2+4l^2-8l\theta-32k+4} \tag{8}$$

$$q^* = \frac{(-Dl-B)\theta+Bl+D}{8k\theta^2+l^2-2l\theta-8k+1} \tag{9}$$

Substituting the above optimal solutions into Equations (1) and (2), the expressions of π_R^D and π_M^D can be calculated as follows:

$$\pi_R^D = \frac{1}{16(8k\theta^2 + l^2 - 2l\theta - 8k + 1)}(-64(\theta + 1)(-2BD\theta + (e_n^2 + e_r^2)p_c^2 + (-2Q_n e_n - 2Q_r e_r + 2c_n e_n + 2e_r(c_r + c_u))p_c + Q_n^2 + Q_r^2 - 2Q_n c_n - 2(c_r + c_u)Q_r + c_n^2 + (c_r + c_u)^2)(\theta - 1)k^2 + 16(\theta + 1)(-Dl + B)^2(\theta - 1)k + (-Dl + B)^2(l^2 - 2l\theta + 1)) \tag{10}$$

$$\pi_M^D = \frac{1}{8(8k\theta^2 + l^2 - 2l\theta - 8k + 1)}(-8((2\theta e_n e_r - e_n^2 - e_r^2)p_c^2 + 2(4E\theta^2 + (-Q_n e_r - Q_r e_n + c_n e_r + e_n(c_r + c_u))\theta + Q_n e_n + Q_r e_r - c_n e_n - e_r(c_r + c_u) - 4E)p_c + 2(Q_r - c_r - c_u)(Q_n - c_n)\theta - Q_n^2 - Q_r^2 + 2Q_n c_n + 2(c_r + c_u)Q_r - c_n^2 - (c_r + c_u)^2)k + (le_n - e_r)^2 p_c^2 + 2((-Q_n e_n + c_n e_n + 4E)l^2 + (-8E\theta + Q_n e_r + Q_r e_n - c_n e_r - e_n(c_r + c_u))l - Q_r e_r + c_r e_r + c_u e_r + 4E)p_c + ((Q_n - c_n)l - Q_r + c_r + c_u)^2) \tag{11}$$

where $A = e_n p_c + 3Q_n + c_n, B = e_r p_c - Q_r + c_r + c_u$, $C = e_n p_c + Q_n + c_n, D = e_n p_c - Q_n + c_n$ in the above formula.

Proposition 1. When $k > \frac{l^2-2\theta l+1}{8(1-\theta^2)}$ and $l > \theta$, the impact of the cost coefficient of quality improvement investment on optimal decision-making is presented below:

(i) $\frac{\partial \omega_n^*}{\partial k} < 0, \frac{\partial \omega_r^*}{\partial k} < 0,$

(ii) $\frac{\partial p_n^*}{\partial k} < 0, \frac{\partial p_r^*}{\partial k} < 0,$

(iii) $\frac{\partial q^*}{\partial k} < 0,$

(iv) $\frac{\partial D_n^*}{\partial k} < 0, \frac{\partial D_r^*}{\partial k} < 0.$

Proof. See Appendix A.

Proposition 1 demonstrates that an increase in the cost coefficient of quality improvement investment leads to a reduction in the degree of product quality upgrading when the remanufactured product quality improvement discount coefficient exceeds the substitution degree of new and remanufactured products. This occurs because, although the quality improvement of remanufactured products is inferior to that of new products, consumers will not significantly shift to new products due to this disparity. As a result, the marginal benefit from quality improvement approaches stability, while a higher cost coefficient elevates the manufacturer's input costs. Constrained by the objective of profit maximization, manufacturers are compelled to lower the degree of product quality upgrading. A diminished degree of quality upgrading reduces the product's added value. Even if manufacturers lower wholesale prices and retailers subsequently reduce retail prices, the negative impact of weakened product competitiveness cannot be effectively offset. As a result, market demand declines in tandem. This finding challenges the conventional belief that price reductions stimulate demand. This proposition further emphasizes that, in the process of upgrading product quality, priority should be given to the dynamic compatibility between the investment scale cost coefficient, the actual benefits generated by the quality improvement, and evolving market demand, rather than merely aiming to minimize investment costs.

Proposition 2. The impact of the carbon trading price on optimal decision-making is presented below:

(i) if $k > \frac{l^2-2\theta l+1}{8(1-\theta^2)}$, $\frac{\partial q^*}{\partial p_c} < 0$,

(ii) if $\frac{l^2-2\theta l+1}{8(1-\theta^2)} < k < \frac{l^2 e_n-3e_n\theta l+le_r-e_r\theta+2e_n}{8(1-\theta^2)e_n}$ and $le_n > e_r$, $\frac{\partial \omega_n^*}{\partial p_c} < 0$, $\frac{\partial \omega_r^*}{\partial p_c} < 0$, $\frac{\partial p_n^*}{\partial p_c} < 0$, $\frac{\partial p_r^*}{\partial p_c} > 0$,

(iii) if $k > \frac{-4l^2 e_r+5e_r\theta l-e_r+3l^2 e_n\theta-3le_n}{8(\theta^2-1)e_r}$ and $le_n > e_r$, $\frac{\partial \omega_n^*}{\partial p_c} > 0$, $\frac{\partial \omega_r^*}{\partial p_c} > 0$, $\frac{\partial p_n^*}{\partial p_c} > 0$, $\frac{\partial p_r^*}{\partial p_c} > 0$.

Proof. See Appendix B.

Proposition 2 indicates that an increase in carbon trading prices leads to a reduction in the degree of product quality upgrading. This is because quality improvement typically requires greater resource input during the production process, which results in higher carbon emissions. Consequently, manufacturers either have fewer carbon allowances available for sale or must purchase additional emission quotas. When carbon trading prices rise, both scenarios diminish manufacturer's profitability, thereby lowering the degree of quality upgrading. When the cost coefficient of quality upgrading investment remains within a certain threshold, the reduced degree of quality upgrading weakens product competitiveness. In such cases, even with rising carbon trading prices, manufacturers are compelled to lower product prices to sustain market competitiveness. As a result, both the wholesale and retail prices of the product decline. When the cost coefficient of the quality upgrading investment surpasses a certain threshold, the combined effect of revenue loss due to rising carbon trading prices and the additional burden of quality improvement costs compels manufacturers to increase wholesale prices to offset the expenses. In turn, retailers adjust retail prices upward through the cost transmission mechanism within the CLSC. Consequently, product prices tend to rise in response to increases in carbon trading prices.

4.2. The centralized model (Model C)

In Model C, the retailer and manufacturer make decisions collectively, and information is fully shared to improve the efficiency of CLSC decision-making. The overall profit of the supply chain can be formulated as follows:

$$\pi_C^C = (p_n - c_n)D_n + (p_r - c_r - c_u)D_r - p_c[(e_n D_n + e_r D_r) - E] - kq^2 \tag{12}$$

According to the principle of reverse reasoning, the optimal solutions are presented when $k > \frac{l^2-2\theta l+1}{4(1-\theta^2)}$, as follows:

$$p_n^{**} = \frac{4kC\theta^2 + ((-3e_n p_c - Q_n - 3c_n)l - B)\theta + Cl^2 + Bl - 4Ck + 2e_n p_c + 2c_n}{8k\theta^2 + 2l^2 - 4l\theta - 8k + 2} \tag{13}$$

$$p_r^{**} = \frac{(-D\theta+2B+2Q_r)l^2 + (-3(B+6Q_r)\theta + D)l + (4k\theta^2 - 4k - 1)(B+2Q_r)}{8k\theta^2 + 2l^2 - 4l\theta - 8k + 2} \tag{14}$$

$$D_n^{**} = \frac{(-4B\theta+4D)k + (-Dl+B)l}{8k\theta^2 + 2l^2 - 4l\theta - 8k + 2} \tag{15}$$

$$D_r^{*} = \frac{(-4D\theta+4B)k + Dl - B}{8k\theta^2 + 2l^2 - 4l\theta - 8k + 2} \tag{16}$$

$$q^{**} = \frac{(-Dl-B)\theta + Bl + D}{4k\theta^2 + l^2 - 2l\theta - 4k + 1} \tag{17}$$

Substitute the above optimal solutions into Equation (12), and the expression of π_C^C can be obtained as follows:

$$\pi_C^C = \frac{1}{16k\theta^2+4l^2-8l\theta-16k+4}(((8\theta e_n e_r - 4e_n^2 - 4e_r^2)p_c^2 + (16E\theta^2 + (-8Q_n e_r - 8Q_r e_n + 8c_n e_r + 8e_n(c_r + c_u))\theta + 8Q_n e_n + 8Q_r e_r - 8c_n e_n - 8e_r(c_r + c_u) - 16E)p_c + 8(Q_r - c_r - c_u)(Q_n - c_n)\theta - 4Q_n^2 - 4Q_r^2 + 8Q_n c_n + 8(c_r + c_u)Q_r - 4c_n^2 - 4(c_r + c_u)^2)k + (le_n - e_r)^2 p_c^2 + ((-2Q_n e_n + 2c_n e_n + 4E)l^2 + (-8E\theta + 2Q_n e_r + 2Q_r e_n - 2c_n e_r - 2e_n(c_r + c_u))l - 2Q_r e_r + 2c_r e_r + 2c_u e_r + 4E)p_c + ((Q_n - c_n)l - Q_r + c_r + c_u)^2) \tag{18}$$

Proposition 3. When $k > \frac{l^2-2\theta l+1}{4(1-\theta^2)}$ and $l > \theta$, the impact of the cost coefficient of quality improvement investment on optimal decision-making is presented below:

(i) $\frac{\partial p_n^{**}}{\partial k} < 0, \frac{\partial p_r^{**}}{\partial k} < 0,$

(ii) $\frac{\partial q^{**}}{\partial k} < 0,$

(iii) $\frac{\partial D_n^{**}}{\partial k} < 0, \frac{\partial D_r^{**}}{\partial k} < 0.$

Proof. See Appendix C.

Proposition 3 illustrates that when the remanufactured product quality improvement discount coefficient exceeds the substitution degree of new and remanufactured products, the product prices, degree of quality upgrading, and market demand all decline as the cost coefficient of quality improvement investment increases. The underlying rationale is similar to that in Model D and is therefore not repeated here. It is further observed that with the rise in the cost coefficient, the price of new products decreases more sharply than that of remanufactured products. This is primarily because quality improvement for new products typically demands greater resource input, resulting in higher cost pressure on CLSC participants compared to the processes involved in remanufacturing. In addition, consumers generally hold higher expectations for the quality of new products. Consequently, when an increase in the cost coefficient leads to a reduced degree of quality upgrading, the competitiveness of new products tends to decline more significantly. Therefore, CLSC members often sustain their competitiveness by implementing significant price reductions. In contrast, remanufactured products, due to their relatively low initial pricing and consumers' more flexible expectations regarding quality, experience a less pronounced impact on competitiveness when the degree of quality upgrading declines. As a result, only a moderate price reduction is necessary.

Proposition 4. The impact of the carbon trading price on optimal decision-making is presented below:

(i) if $k > \frac{l^2-2\theta l+1}{4(1-\theta^2)}$, $\frac{\partial q}{\partial p_c}^{**} < 0$,

(ii) if $\frac{l^2-2\theta l+1}{4(1-\theta^2)} < k < \frac{l^2 e_n-3e_n\theta l+le_r-e_r\theta+2e_n}{4(1-\theta^2)e_n}$ and $le_n > e_r$, $\frac{\partial p_n}{\partial p_c}^{**} < 0$, $\frac{\partial p_r}{\partial p_c}^{**} > 0$,

(iii) if $k > \frac{l^2\theta e_n+3e_r\theta l-le_n-e_r-2l^2 e_r}{4(\theta^2-1)e_r}$ and $le_n > e_r$, $\frac{\partial p_n}{\partial p_c}^{**} > 0$, $\frac{\partial p_r}{\partial p_c}^{**} > 0$.

Proof. See Appendix D.

Proposition 4 demonstrates that both the carbon trading price and the cost coefficient of quality upgrading investment significantly influence the degree of product quality improvement and the product prices. To maintain market equilibrium between supply and demand, governments could implement differentiated carbon quota allocations based on varying levels of investment cost coefficients, thereby alleviating the pressure of sharp increases in their carbon costs. Moreover, targeted subsidies for quality upgrading or tax incentives can be introduced to reduce the investment costs associated with quality improvements. This, in turn, would enable firms to sustain a reasonable level of quality enhancement even in the face of rising carbon trading prices.

4.3. Revenue sharing contract (RSC) coordination

Based on optimal decision-making, when the cost coefficient of quality improvement investment exceeds a certain threshold, the product sales price increases with rising carbon trading prices, enabling both retailers and manufacturers to benefit simultaneously. However, the degree of product quality upgrading declines because manufacturers bear the costs of both quality improvement and carbon emissions. Therefore, to motivate manufacturers to improve product quality, we propose an RSC to coordinate the CLSC. The contract refers to the retailer's distribution of sales revenue to the manufacturer according to the ratio $1-\phi$, which is recorded as the Y model.

In the Y model, the profits of retailers and manufacturers are as follows:

$$\pi_R^Y = \phi(p_n D_n + p_r D_r) - \omega_n D_n - \omega_r D_r \tag{19}$$

$$\pi_M^Y = (1-\phi)(p_n D_n + p_r D_r) + (\omega_n - c_n)D_n + (\omega_r - c_r - c_u)D_r - p_c[e_n D_n + e_r D_r - E] - kq^2 \tag{20}$$

According to the principle of reverse reasoning, the optimal solutions can be expressed as follows:

$$ {p_n}^Y = \frac{\phi Q_n + \phi q + \omega_n}{2\phi} \tag{21} $$

$$ pr^Y = \frac{\phi Q_r + l\phi q + \omega_r}{2\phi} \tag{22} $$

To enhance the operation efficiency of the CLSC and profitability of members, we set ${p_n}^Y = {p_n}^{**}$,${p_r}^Y = {p_r}^{**}$, ${q_n}^Y = q^{**}$ and he following equations can be further obtained:

$$ \omega_n^Y = \phi(c_n + p_c e_n) \tag{23} $$

$$ \omega_r^Y = \phi(c_r + c_u + p_c e_r) \tag{24} $$

To make all CLSC members accept the contract, it is necessary to satisfy $\pi_M^{Y*} \geq \pi_M^{D*}$ and $\pi_R^{Y*} \geq \pi_R^{D*}$, and the contract parameters are as follows:

$$ \phi \geq \frac{((\theta^2-1)k+2J)^2(8(\theta^2-1)(-2BD\theta+(e_n^2+e_r^2)p_c^2-2Gp_c+F)k^2-2k(\theta^2-1)(B-Dl)^2-(B-Dl)^2J)}{8((\theta^2-1)k+J)^2(4(\theta^2-1)(-2BD\theta+(e_n^2+e_r^2)p_c^2-2Gp_c+F)k^2-2k(\theta^2-1)(B-Dl)^2-2(B-Dl)^2J)}, $$

$$ \phi \leq \frac{((\theta^2-1)k+2J)(4(\theta^2-1)(-2BD\theta+(e_n^2+e_r^2)p_c^2-2Gp_c+F)k^2-3k(\theta^2-1)(B-Dl)^2-2(B-Dl)^2J)}{8((\theta^2-1)k+J)(2(\theta^2-1)(-2BD\theta+(e_n^2+e_r^2)p_c^2-2Gp_c+F)k^2-k(\theta^2-1)(B-Dl)^2-(B-Dl)^2J)}, $$

where $F = Q_n^2 + Q_r^2 - 2c_nQ_n - 2Q_r(c_r + c_u) + c_n^2 + (c_r + c_u)^2$,$G = Q_ne_n + Q_re_r - c_ne_n - e_r(c_r + c_u)$,$J = \frac{l^2-2l\theta+1}{8}$ in the above formula.

5. Numerical study

5.1. Parameter setting

It is of great importance to enhance the quality of products to satisfy consumer demand and to adapt to the fiercely competitive market environment. In recent years, enterprises have actively engaged in quality improvement, aiming to align products with the evolving preferences of customers, such as, Samsung, Amazon, and Best Buy [47,48]. The analysis of the model shows that the degree of quality upgrading and carbon trading price have a significant effect on CLSC decision-making. In order to investigate the detailed influence of them on decisions, this paper employs iPhone14 as an example to verify the relevant conclusions of the above model through numerical analysis. The total carbon emissions of iPhone14, from the extraction of raw materials, through the manufacturing process, packaging, transportation, utilization, and recycling, are 61 kg. The most carbon emissions are concentrated in the manufacturing process, accounting for 79% of the total. The second is the use of links, about 18%, while transportation and scrap processing account for less than 3%. Compared with new products, remanufacturing can not only reduce the negative environmental impact by 80% but also reduce the cost by 50% [19]. In order to simplify the simulation process, this paper sets e_n = 50, e_r = 30, c_n = 30, c_r = 15. This article also refers to Wang et al. [9] and Giri et al. [49] and adjusts their approaches. The relevant parameters are as follows :Q_n = 300, Q_r = 200, c_n = 30, c_r = 15, c_u = 10, e_n = 50, e_r = 30, l = 0.8, θ = 0.5, E = 4000.

5.2. Sensitivity analysis

(1) The impact of p_c and k on the price under Model D

As illustrated in Figures 2 and 3, as both the cost coefficient of quality improvement investment and the carbon trading price increase simultaneously, the wholesale and retail prices of the product initially decline and subsequently rise. In the early stage of this concurrent increase, the compounded cost pressures, stemming from both quality improvement investments and carbon emissions, lead manufacturers to reduce the degree of quality upgrading. This reduction directly undermines the product's core competitiveness. To sustain consumer purchasing intent, manufacturers are compelled to lower wholesale prices, which prompts retailers to follow suit with retail prices, thereby initiating a downward pricing trend. As both factors continue to escalate, the combined cost pressure gradually exceeds the manufacturers' capacity for internal absorption. Maintaining low prices under such circumstances would result in a substantial erosion of profits. Consequently, manufacturers are forced to transfer the rising costs by increasing wholesale prices, and retailers, facing higher procurement expenses, correspondingly raise retail prices, ultimately driving product prices into an upward phase. At the same time, Figure 2 and 3 show that in any case, the price of remanufactured products remains consistently lower in comparison to that of new products. This is due to the fact that even if the same degree of quality upgrading is applied, the inevitable inferiority of remanufactured products compared to new ones results in a slightly lower pricing for the remanufactured items. Consequently, it is reasonable to deduce that the price of remanufactured products is lower than that of new products.

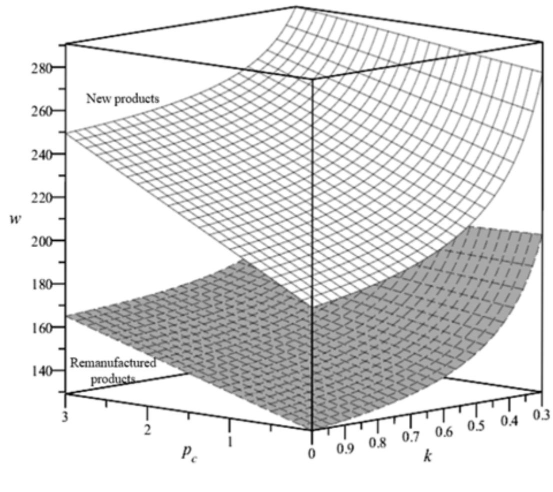

Figure 2. The wholesale price of new products and remanufactured products under Model D varies with p_c and k.

(2) The influence of p_c and k on the profit of CLSC members under Model D

As demonstrated in Figures 4 and 5, the manufacturer's profit initially declines and then increases as both the cost coefficient of quality improvement investment and the carbon trading price rise, while the retailer's profit shows a continuous downward trend. In the early stage, although some cost savings are achieved by reducing the degree of quality upgrading, the overall cost increase outweighs these savings. Additionally, the decline in product quality diminishes competitiveness, compelling the manufacturer to lower prices to sustain consumer purchasing intent. This dual pressure on both the revenue and cost sides results in an initial drop in profit margins. As the two factors continue to rise, the manufacturer partially offsets the increased costs by moderately raising the wholesale price. Combined with the cost savings from a lower degree of quality upgrading, this ultimately leads to a recovery in profits. Retailers are persistently subjected to dual pressures. On the one hand, declining wholesale prices lead to corresponding drops in retail prices, directly compressing profit margins. When wholesale prices rise, procurement costs increase while limited pricing flexibility prevents retailers from passing on the costs. On the other hand, the ongoing decline in product quality dampens consumer purchasing intent, placing downward pressure on retail sales volume. As a result of this dual squeeze, profits have continued to erode.

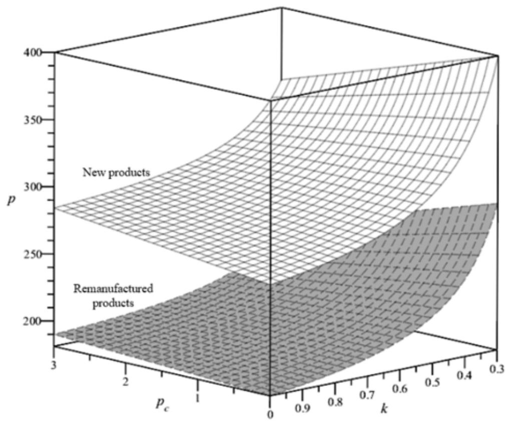

Figure 3. The retail price of new products and remanufactured products under Model D varies with p_c and k.

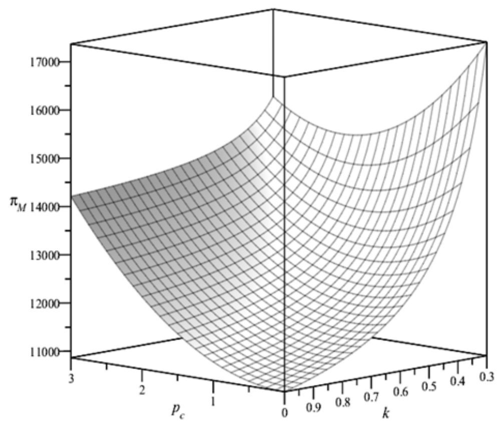

Figure 4. Under Model D, the manufacturer's profit π_M changes with p_c and k.

(3) The effect of p_c and k on the retail price under Model C

It is observed in Figure 6 that, under centralized decision-making, the retail prices of both new and remanufactured products increase as both the cost coefficient of quality improvement investment and the carbon trading price rise simultaneously. This outcome is primarily attributed to the high degree of interest alignment between manufacturers and retailers in a centralized decision-making framework, where decisions are made with an integrated focus on minimizing overall operational costs and maximizing total profit. The concurrent increase in these two factors leads to a direct escalation in the total cost of the CLSC. To sustain overall profitability, CLSC participants pass the compounded cost pressure onto end consumers by raising retail prices to offset the additional costs. Consequently, the retail prices of both new and remanufactured products rise in tandem with the simultaneous increase in these cost drivers.

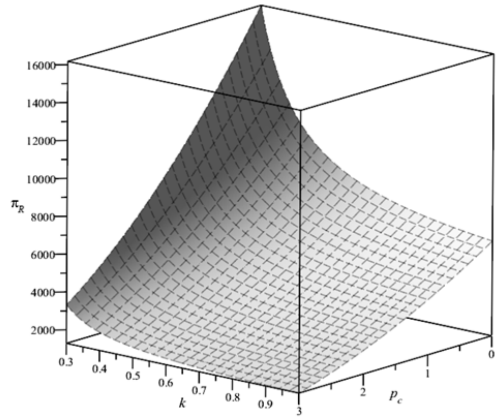

Figure 5. Under Model D, the retailer profit π_R changes with p_c and k.

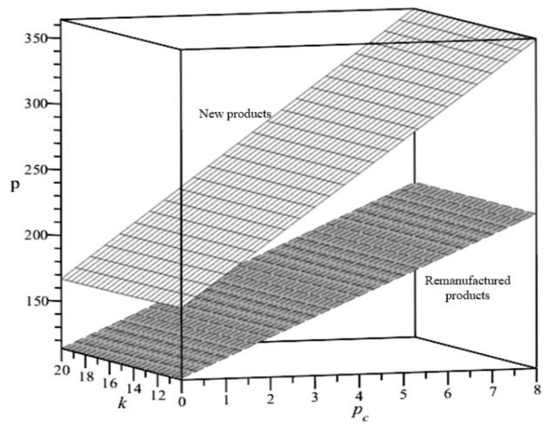

Figure 6. The optimal retail prices vary with k and p_c under Model C.

(4) The influence of p_c and k on supply chain profit π_C under Model C

It is shown in Figure 7 that, supply chain profits initially decline and then rise as both the cost coefficient of quality improvement investment and the carbon trading price increase simultaneously. In the early phase of this joint increase, cost pressures are mitigated by raising product prices. However, this strategy leads to reduced consumer willingness to purchase, resulting in suppressed sales volumes. Despite the price adjustments, total revenue remains insufficient to cover the rising costs, leading to a decline in profits. As both factors continue to rise, CLSC members respond by lowering the degree of quality upgrading to more effectively reduce associated costs and partially alleviate financial pressure. At the same time, further price increases are implemented to transfer the remaining cost burden to the market. Driven by dual cost-reduction pressures, the overall profitability of the CLSC has been restored and further enhanced, ultimately resulting in a turnaround from declining to growing profits.

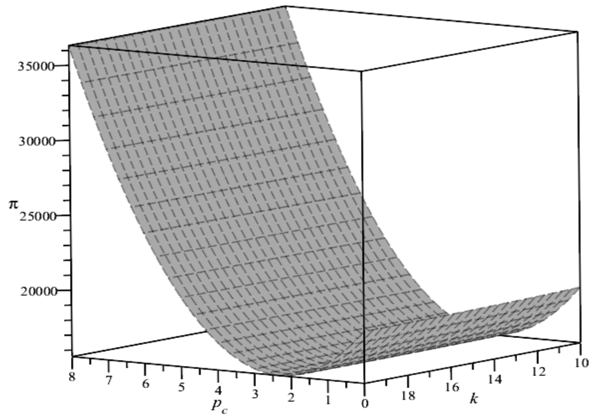

Figure 7. The changes of supply chain profit π_C with p_c and k under Model C.

5.3. Contract validity analysis

This section tests the effectiveness of the RSC. According to 4.3, the interval range of the revenue sharing ratio is $0.1674 \leq \phi \leq 0.4091$. In accordance with the above relationship, assuming $\phi = 0.3$, the coordination results are presented in Table 3.

Table 3. Optimal decisions under the coordination contract.

Parameter	Decentralized model	Centralized model	Coordination model
q	46.1842	113.2258	113.2258
ω_n	190.5921	--	10.5000
ω_r	132.4737	--	8.4000
p_n	268.2882	224.1129	224.1129
p_r	184.7105	159.2903	159.2903
D_n	68.9035	164.6237	164.6237
D_r	17.7851	48.9785	48.9785
π_R	6289.4578	--	11268.8580
π_M	11059.2324	--	15155.9270
π_C	17348.6902	26424.7850	26424.7850

According to the data analysis presented in Table 3, the following insights can be determined. (1) Under this contract, the degree of quality upgrading increases, while product prices decline to a reasonable level. This indicates that the contract enhances product attractiveness by improving product quality and appropriately reducing prices, thereby improving the operational efficiency of the entire supply chain. (2) In light of the preceding analysis, a decentralized decision-making scenario faces the dilemma in which price reductions fail to stimulate market demand. Under this coordination mechanism, however, the improvement in quality upgrading and the reasonable decline in prices lead to a significant increase in market demand for both new and remanufactured products compared with the low levels observed under decentralized decision-making, thereby effectively overcoming the limitations in such a structure.

As shown in Figures 8–10, under this revenue sharing contract, the profits of both the manufacturer and the retailer, as well as the overall supply chain profit, are higher than those under the uncoordinated scenario, indicating the effectiveness of the revenue sharing mechanism. Furthermore, Figure 11 illustrates that as the contract parameter increases, the retailer's profit rises gradually, while the manufacturer's profit decreases correspondingly. This phenomenon can be attributed to the increase in contract parameters, which results in an increase in the proportion of sales revenue received by retailers and a decrease in the proportion of sales revenue obtained by manufacturers. But in a certain range, the manufacturer's profit exceeds that of the retailer. Therefore, it is recommended that retailers engage in more effective communication with the supply chain, ensuring the appropriate sharing of information in order to facilitate a mutually beneficial outcome.

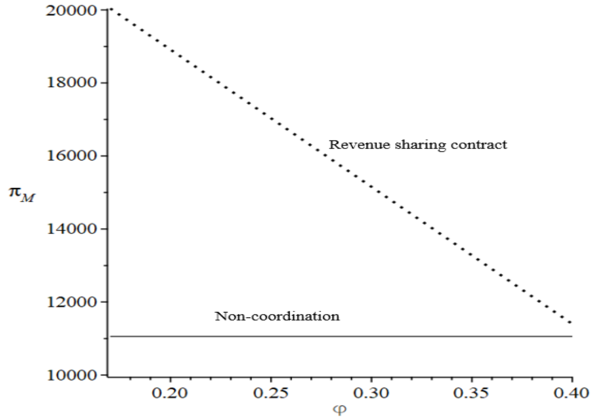

Figure 8. Comparison of manufacturer's profits under non-coordination and revenue sharing contract scenarios.

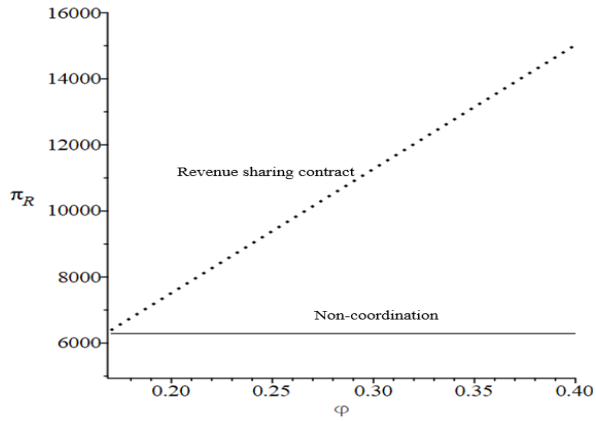

Figure 9. Comparison of retailer's profits under non-coordination and revenue sharing contract scenarios.

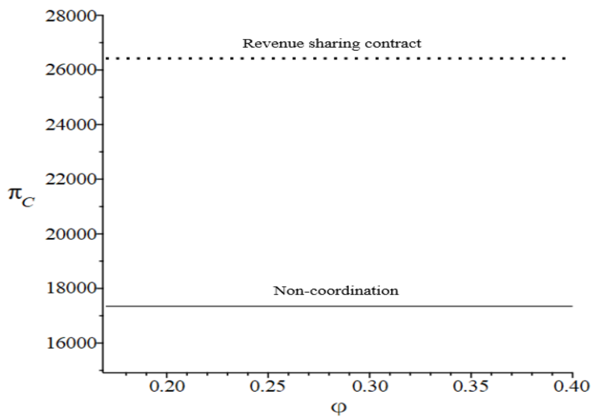

Figure 10. Comparison of CLSC profits under non-coordination and revenue sharing contract scenarios.

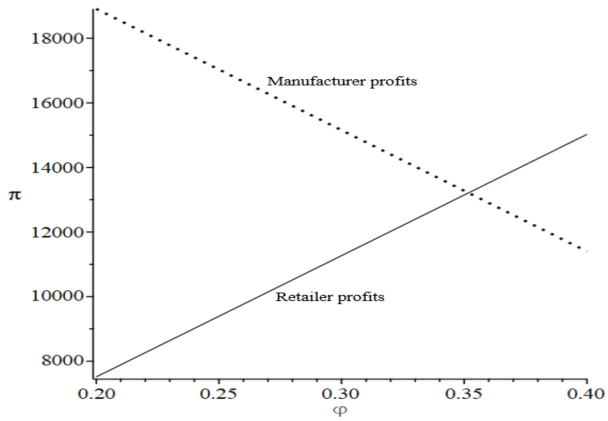

Figure 11. Profits of manufacturer and retailer change with ϕ under revenue sharing contract.

In conclusion, when the contract parameters are situated within a specific range, the profitability of manufacturers and retailers is greater than that of those operating without contracts. This demonstrates that the introduction of a contract can enhance the enthusiasm and willingness of both parties to cooperate. Consequently, both parties are inclined to enter into such agreements. Further, through in-depth communication and negotiation, both parties may establish a mutually satisfactory equilibrium based on their respective interest demands and risk tolerance.

6. Research implications

In recent years, there has been an increasing focus among consumers on product quality. Moreover, in some industries, quality has become the second largest factor influencing consumers' purchase decisions, second only to the price of products [50]. Therefore, numerous industries have adopted the strategy of quality improvement as a means of competing in the marketplace to meet the level of consumer expectations, and corporations may lose commercial reputation if they fail to meet consumer expectations [51]. For example, the signal problem of early Apple mobile phones has been criticized by some users. After that, Apple has continuously improved and optimized the antenna design and signal receiving module in the development process of new mobile phones, which has improved the overall signal quality of mobile phones. In addition, Apple has also persistently enhanced the imaging quality of mobile phone cameras and battery life. Through this series of product quality improvement measures, Apple has further met consumers' expectations for the quality of mobile phones, which has not only stabilized the old user groups, but also attracted more new customers. It has always maintained a high market share and good brand reputation in the global mobile phone market.

Combining the above cases and our research model, we consider the effect of varying degrees of quality upgrading in new and remanufactured products on the CLSC and provide valuable insights into the pricing strategies of CLSC members under the CATR. The study proposes the following management implications.

(1) An increase in the cost coefficient of quality improvement investment has been shown to reduce the degree of quality improvement, thereby diminishing product market demand. To address this, manufacturers can implement lean production methods to streamline quality enhancement processes and eliminate redundant inputs. Simultaneously, the adoption of intelligent equipment can improve upgrading efficiency and reduce unit costs. It is crucial that quality improvement efforts are not entirely abandoned due to cost pressures. Suspending upgrades may cause products to fall behind evolving market expectations, ultimately leading to a loss of market share. In addition, to mitigate this risk, the government can introduce targeted subsidies for quality improvement, offering financial support for manufacturers' equipment renewal. Such measures not only ease the financial burden on manufacturers but also reinforce a commitment to quality enhancement, enabling firms to pursue quality improvements while managing costs, and thereby maintain a balance between product competitiveness and market demand.

(2) It has been observed that when the cost coefficient of quality improvement investment remains within a certain threshold, an increase in carbon trading price leads to a decrease in both product prices and supply chain profits under the CATR, which may cause manufacturers to decrease the production proportion of remanufactured products. Therefore, governments ought to take the lead in implementing green procurement policies, encouraging consumers to prioritize the procurement of remanufactured products. More carbon quotas are allocated to manufacturers that produce remanufactured products. Manufacturers should subdivide the market according to the differences in awareness for environmental protection products among different consumer groups. In the meantime, they can create a distinctive brand of remanufactured products and enhance the brand image and market influence by disseminating environmental protection concepts. These measures not only create a stable market demand for remanufactured products but also encourage manufacturers to expand the production scale of remanufactured products.

(3) The RSC is introduced to coordinate Model D so that it can reach the level of Model C. The profit after coordination is greater than that of Model D. Hence, it is recommended that retailers engage in active collaboration with manufacturers, which not only facilitates the enhancement of their profits but also enhances customer satisfaction and loyalty by optimizing CLSC processes. This, in turn, facilitates the expansion of market share and brand influence. Nevertheless, during the implementation phase, potential risks of information asymmetry may arise for manufacturers, as retailers might withhold actual sales data to serve their own interests. At this stage, a digital real-time data sharing platform can be established by manufacturers to enable the synchronization of key information, such as retailers' sales revenue and order records, with their own systems, thereby removing information barriers.

7. Conclusions

To determine the influence of quality improvement on the CLSC and explore how to coordinate the interests of CLSC members by designing a contact mechanism under the CATR, this paper constructs Model D and Model C. Through the comparative analysis of the parameters of the two models, the RSC is introduced to harmonize the CLSC. Furthermore, to further explore the specific impact of unit carbon trading price and the cost coefficient of quality improvement investment on pricing and profit decision-making, this paper employs the numerical simulation method, gaining deeper insight into the aforementioned issues. The research conclusions are as follows.

(1) As the cost coefficient of quality improvement investment increases, manufacturers' incentives to improve product quality diminish, ultimately resulting in a decline in the degree of quality upgrading. This reduction directly diminishes the added value of products and, subsequently, weakens consumer purchase intentions. Even when manufacturers and retailers lower wholesale and retail prices to stimulate market demand, demand continues to decline. These findings highlight that, in an era where consumers place growing importance on product quality, enterprises must not compromise on quality upgrading efforts due to cost pressures.

(2) With the rise in carbon trading prices, a decline in the degree of quality upgrading has been observed. When the cost coefficient of quality improvement investment remains below a certain threshold, retail and wholesale prices tend to decrease despite higher carbon trading prices, to maintain product competitiveness weakened by insufficient quality improvements. Conversely, once the cost coefficient surpasses that threshold, the compounded pressure necessitates passing on the costs by raising both wholesale and retail prices.

(3) Under the combined influence of carbon trading prices and the cost coefficient of quality improvement investment, variations in CLSC performance are observed across different decision-making models. In the decentralized model, as both factors increase simultaneously, wholesale and retail prices initially decline before rising. A similar trend is observed in the manufacturer's profit, which first decreases and then increases, while the retailer's profit shows a continuous downward trajectory. In the centralized model, product prices steadily rise with the increase in both factors, whereas the CLSC profit first declines and then rebounds.

(4) The RSC is introduced to coordinate the model under decentralized decision-making. The retailers give their sales income to manufacturers in a certain proportion. It is pointed out that the profit of all CLSC members after coordination is greater, and the coordination of the CLSC is realized.

However, it should be noted that this paper is not without limitations. First, we only consider a single manufacturer for quality improvement, but in the real competitive market environment, there may be two competing manufacturers for product quality improvement. Second, the impact of quality improvement on the CLSC has been examined only under the CATR. In practice, to strengthen environmental governance, governments often implement multiple carbon-related policy instruments that work together to achieve coordinated regulation. Finally, we solely propose the implementation of an RSC for the purpose of coordination. In practice, there are various forms of contracts, such as cost-sharing contracts and quantity discount contracts. Each contract possesses distinctive applicable scenarios and advantages. These contracts may be employed alone or in combination to achieve more effective coordination. Therefore, future research may be extended from the following three aspects. (1) The effect of two competing manufacturers' simultaneous quality improvement on CLSC decision-making can be examined in the future. (2) Future research will focus on developing an integrated carbon policy model to examine how the interaction of multiple policies dynamically influences manufacturers' quality upgrading and pricing strategies. (3) By comparing the coordination effect of various forms of contracts, we will explore how a coordination contracts can be designed and combined to achieve a superior coordination effect.

Author contributions

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Conflict of Interest

The authors have no relevant financial or non-financial interests to disclose.

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Data availability statement

Data will be made available upon request.

Use of Generative-AI tools declaration

The authors declare that they did not utilize any artificial intelligence (AI) tools in the creation of this article.

Ethical statement

Ethical approval was not required for this study as it does not involve human or animal experiments.

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