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Decision-Making in a Closed-Loop Supply Chain under Fairness Concerns and Optimal Subsidies

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Abstract: Government subsidies have played an important role in closed-loop supply chain (CLSC) waste utilization. However, when the retailer is disadvantaged in the supply chain cooperation and does not have access to subsidies, fairness issues may arise that affect pricing and subsidies. Therefore, this study aims to examine the optimal solutions for a government-led CLSC with remanufacturing subsidies and fairness concerns. We develop a three-echelon game with a government, a manufacturer, and a fairness-concerned retailer and derive the solutions for four scenarios: the fairness-neutral model, without fairness issues; the retailer has fairness concerns about the distribution of supply chain profits, and the concerned behavior is recognized by the manufacturer; the retailer is fairness-concerned, but the manufacturer ignores the concerned behavior; and the centralized scenario. Through the comparative analysis of different models, we design a cooperation mechanism for enterprises. Then, the conclusions are verified by numerical experiments. This study shows the following: (1) The retailer is always willing to maintain fairness concerns, but this does not affect the amount of collection. (2) The government will consume more subsidies because of the fairness issue ignored by the manufacturer. (3) Only when unit waste pollution is relatively low while the degree of fairness concerns is significant, will the manufacturer recognize the fairness concerns to reduce its unfavorable impact on profit. The increase in the level of concern can bring more benefits for two enterprises by consuming more subsidies for the highly polluting wastes. (4) A two-part tariff contract can coordinate the enterprises and promote social welfare within a certain parameter range.

Keywords: government subsidy; social welfare; game theory; closed-loop supply chain; fairness concerns; coordination mechanism

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1. Introduction

As a result of the constant growth in the world population, non-renewable resources are being consumed at an accelerated pace, and the amount of hard-to-decompose waste in the environment is increasing, which has caused a serious impact on the ecology of the Earth [1]. Discarding end-of-life materials in nature harms the environment and hinders sustainable development [2]. The reuse value of waste materials is widely recognized [3–5]. Using recycled waste for production can reduce the operation costs of companies while improving the environment [6]. The closed-loop supply chain (CLSC) system can reasonably handle waste, maximize the utilization of waste products, and achieve a circular economy [7]. Nowadays, most enterprises tend to implement CLSC strategies to improve operational efficiency [8].

For environmental protection and the circular economy, modern society pays attention to the threat of pollutants and strives to achieve sustainable development. Many governments have implemented subsidies to encourage recycling and remanufacturing. The Chinese government established a fund of subsidies to reward enterprises that recycle and remanufacture electronic waste and retailers that sell remanufactured electrical products [9]. The government of India declared that manufacturers could receive a subsidy fee for producing remanufactured electronic goods [10]. As recycling and remanufacturing are the two basic strategies of CLSC, the operation of CLSC under subsidies has been widely studied [11–13].

Given this backdrop, it is worthwhile to research the fairness concerns issue. To be more specific, members of supply chains prioritize a fair channel profit distribution and maximize their profits [14]. When making decisions, the subordinate firms with less authority consider fairness concerns to increase benefits [9,15]. Furthermore, the subordinate enterprises perceive unfairness because government subsidies are typically received by the leading enterprises [16]. Regardless of the absolute profit of the enterprise, the importance of equity issues is highlighted in the supply chain. Inequitable distribution leads to difficulties in maintaining cooperative relationships between enterprises. For instance, Procter & Gamble lost its partnership with the subordinate dealer Xuzhou Wanji Trading Co. [17]. It is thus clear that how the lead company handles equity issues is critical to the long-term interests of supply chain companies.

There are many existing pieces of literature that have used game theory to study CLSC with government subsidies. Some academics have investigated how government subsidies affect business operations [18–22]. Furthermore, another part of the literature studied the influence of selecting different subsidy policies and recipients [1,23,24]. There are also studies about the game of supply chain fairness issues [16,25,26], as well as studies considering the attitude of the leading enterprise when the subordinate enterprise is concerned about fairness [25,26]. However, fairness issues and government optimal subsidies need to be analyzed jointly in CLSC decision-making, which has not been considered by scholars before.

Motivated by the above issues, this paper develops the Stackelberg game models of the government-led CLSC, which contain the government, a manufacturer, and a retailer with fairness concerns. As a subordinate enterprise, the retailer sells the manufacturer's products to consumers and recycles waste products for the manufacturer. The manufacturer remanufactures waste products and the government offers the manufacturer the remanufacturing subsidy. Three-stage Stackelberg game models are established to address the following problems:

(1) How does the fairness issue influence pricing decisions and optimal subsidy in CLSC?
(2) What attitude will enterprises choose to treat fairness concerns in the government-led CLSC?
(3) In light of government subsidy and the subordinate retailer's fairness concerns, how can supply chain companies achieve coordination?

The main contributions of this study include the following three points. First, this study is the first to introduce enterprise fairness concerns and government remanufacturing subsidy into the three-echelon CLSC game by proposing four pricing models and analyzing their equilibrium solutions. Second, this study finds the enterprises' choice of pricing models under different levels of retailer fairness concerns and unit waste pollution. Third, this study designs a two-part tariff pricing contract to coordinate upstream and downstream firms, providing them with the opportunity to achieve a win–win situation under fairness concerns and optimal government subsidies. The analysis results and research ideas in this paper provide a decision basis for enterprise pricing and government subsidies under the fairness concerns of the subordinate enterprise in CLSC, which is beneficial to the practice of CLSC cooperation.

The remaining parts of this study are organized as follows. We briefly review related studies in Section 2. The model description is provided in Section 3. Section 4 solves and

analyzes the optimal solutions of game models. Section 5 provides a coordination mechanism for enterprises. Section 6 uses numerical analysis to validate the main conclusions. Finally, the major findings are summarized in the last section. All solution processes and proofs are offered in Appendix A.

2. Literature Review

The related studies could be separated into two categories: (1) CLSC management under government subsidy and (2) fairness concerns and coordination in the supply chain.

2.1. CLSC Management under Government Subsidy

Government subsidies are essential to economic sustainability. Much literature on CLSC with government subsidies has focused on the effects of subsidies and the choice of subsidy objects. Mitra and Webster [27] developed a two-stage game model for CLSC. The findings suggested that subsidies can encourage remanufacturing activities, and the subsidy-sharing policy is more beneficial to improving the utilization of waste. Long et al. [20] considered the green preference of consumers and the green sensitivity of enterprises together. They formulated Stackelberg game models dominated by the retailer and the manufacturer under government price subsidies, respectively. Their findings indicated that increasing consumer price subsidies benefit social welfare and the demand for green products. The study also pointed out that, from a social welfare standpoint, the government needs to improve the green sensitivity of the subordinate enterprise rather than that of the leader. Feng et al. [11] suggested that government subsidies can enhance the ability of firms to remanufacture and avoid a rapid drop in the quality level of new items owing to the growth in refurbished product quality. Liu and Wang [21] studied CLSC of power batteries, considering recycling subsidies and recycling channel encroachment. They found that subsidies and channel encroachment positively affect recycling activities, where the subsidy and channel cost levels are important factors for social welfare and corporate benefits. Shan et al. [22] discussed the impact of service budgets, recovery subsidies, and different forms of recovery on decision-making. The study found that, as soon as the service budget allows, the retailer recycling model has the highest recovery efficiency and social welfare.

Most of the above literature reflects the positive role of government subsidies. However, some scholars found that subsidies may not be beneficial in all aspects. Ma et al. [28] introduced consumer subsidies into a dual-channel CLSC. They revealed that consumption subsidies might reduce the earnings of the e-tailer while benefiting other supply chain members and consumers. He et al. [19] studied supply chain pricing and sales channel selection under subsidies for remanufactured products. They found that the supply chain structure changes according to the guidance of government subsidies. Although increasing subsidies brings higher benefits to consumers and enterprises, it may harm the environment.

On the other hand, the impacts of choosing different objects to subsidize are also a research hot spot. Jena et al. [23] analyzed the profits of CLSC across different scenarios, where the government subsidizes both the collector and the manufacturer, only the retailer, only the consumers, and only the collector. Their results indicated that the government could maximize the total surplus and profits of CLSC by providing subsidies to the manufacturer. Wan and Hong [24] constructed game models for CLSC with two recycling channels under subsidies. They demonstrated that the effects of the recycling subsidy and remanufacturing subsidy on product price, recycling rate, and economic profits are the same. Zhao et al. [13] constructed CLSC models with different government subsidy objects based on the context of the new power automobile industry. Using the game theory method, they analyzed optimal solutions of enterprises across five subsidy scenarios. Zhang et al. [29] developed CLSC of WEEE and analyzed the impacts of fund policies on CLSC and society. In their opinion, the most effective way is for the retailer to engage in remanufacturing with the government's subsidy plan. Similar to Zhang et al., Ma [1] found that the government subsidizing the retailer can lead to a lower sales price and a higher

level of recoveries and profits than subsidizing other objectives. Huang and Liang [30] formulated three recycling models in CLSC considering government subsidies (online recycling of the remanufacturer, offline recycling of the recycler, and dual-channel recycling). They indicated that, when the government reasonably distributes subsidies between the two enterprises, the two-channel recovery model is most beneficial to the remanufacturer.

2.2. Fairness Concerns and Coordination in the Supply Chain

Existing literature has shown valuable perceptions about operation and cooperation in the supply chain within the context of fairness issues. The study of Cui et al. [31] was the first to combine the analysis of CLSC operations with fairness concerns. They suggested that enterprises coordinate with a wholesale price contract. Based on this research, scholars have conducted many extended studies. Li and Li [32] constructed a manufacturer-led CLSC with two channels and found that the retailer makes more profits through fairness concerns, which causes a decline in the manufacturer's benefits and the channel's efficiency. Differently from Cui et al., their results show that, when the retailer offers product services, the effect of the wholesale price contract is not ideal. Shu et al. [26] constructed CLSC containing a manufacturer, a retailer, and a fairness-concerned collector. They analyzed the solutions for different scenarios involving fairness issues, and then a two-part tariff contract was deployed to accomplish coordination. It is worth mentioning that this paper creatively considered the situation in which the manufacturer ignores the recycler's concern about the profit gap with the fairness issue. Similarly, Li et al. [25] point out that, when the manufacturer disregards the retailer's fairness concerns, both market demand and recovery revenue decline.

Furthermore, some academics focused on the relationship between equity concerns and environmental issues. For example, Liu et al. [17] found that the retailer increases its profit through fairness concerns while reducing the manufacturer's benefits and enthusiasm for emission reduction. They also pointed out that the altruistic preference of the manufacturer is more effective than the fairness concern of the subordinate enterprise in balancing distribution and environmental protection. Jian et al. [33] indicated that the fairness concerns of the subordinate firms are not conducive to the products' environmental performance and the channel benefit. They designed a profit-sharing mechanism that benefits the common interests of enterprises and improves the green level of products. Wang et al. [34] indicated that, when manufacturers produce common products in the supply chain, manufacturers and retailers can obtain higher utility through fairness concerns, and the fairness-neutral scenario is a win–win choice. In contrast, when the supply chain chooses green products, retailers can achieve Pareto optimization by adjusting their cost coefficients without damaging the utilities of manufacturers by maintaining fairness concerns.

Some scholars considered fairness concerns and government subsidies in their papers [16,35,36]. Wang et al. [16] studied the operation decision of CLSC containing a manufacturer with corporate social responsibility (CSR) and a fairness-concerned retailer. They found that the coordination of enterprises can be realized within certain parameter ranges by sharing government subsidies and the cost of CSR activity. Shi et al. [35] found that providing green subsidies to both the manufacturer and the retailer can more effectively eliminate the adverse impacts of the fairness issue on environmental protection and channel profits. Han et al. [36] introduced government emission reduction subsidies and fairness issues into the decision-making of a platform-led supply chain. They argued that the manufacturer's fairness concerns offset the positive impacts of subsidies on the demand for environmentally friendly products and supply chain profits. They also designed a joint sharing contract of profits and costs, which can help the supply chain achieve coordination to some extent.

As far as we know, only one study considers both the government subsidies and fairness problems in CLSC management [16]. They aimed to examine the optimal solutions and coordination of firms under government subsidies, CSR behavior, and fairness concerns.

However, they did not set subsidies as a decision variable, like in the study of Liu and Wang [21]. Thus, there is no study that examines the fairness concerns of the subordinate firm in conjunction with the optimal government subsidies, firms' optimal solutions, and coordination in the CLSC model. Therefore, to cover the research gap, this study considers a Stackelberg game model with a government, a manufacturer, and a fairness-concerned retailer. The manufacturer recycles waste products through the retailer and remanufactures them; the government provides a remanufacturing subsidy to the manufacturer to improve social welfare; and the retailer's fairness concerns could be responded to or ignored by the manufacturer [25,26]. This research aims to examine the optimal subsidy, firms' pricing decisions, and coordination conditions in CLSC across different scenarios of fairness concerns. This paper provides a valuable reference for enterprises' rational operational decisions and helps the government set subsidies scientifically under different environmental impacts of waste products and scenarios of fairness concerns. The results of this study are theoretical support for the sustainable development of supply chains under the disturbance of enterprise fairness issues.

2.3. Research Gap

We surveyed the relevant literature for our research in Table 1. It can be seen that no study considers introducing both the fairness problems and the endogenous subsidies of government into CLSC management. This study aims to examine the optimal solutions for a three-echelon CLSC with subsidy and fairness concerns. We summarized the companies' attitudes towards fairness concerns through comparative analysis and designed a coordination approach.

Table 1. Survey on related work.

Author(s)	Stages of Games	CLSC	Subsidy Set	SW	Treatment of FC	Coordination Contract
Mitra and Webster [27]	2	✓	EX	-	-	-
Long et al. [20]	3	✓	EX	✓	-	-
Feng et al. [11]	2	✓	EX	✓	-	-
Liu and Wang [21]	3	✓	EN	✓	-	-
Shan et al. [22]	2	✓	EX	✓	-	-
Ma et al. [28]	2	✓	EX	-	-	-
He et al. [19]	2	✓	EX	✓	-	-
Jena et al. [23]	2	✓	EX	-	-	-
Wan and Hong [24]	2	✓	EX	-	-	-
Zhao et al. [13]	2	✓	EX	-	-	-
Zhang et al. [29]	2	✓	EX	✓	-	-
Ma [1]	2	✓	EX	-	-	-
Huang and Liang [30]	2	✓	EX	-	-	-
Cui et al. [31]	2	-	-	-	R	wholesale price
Li and Li [32]	2	-	-	-	R	wholesale price
Shu et al. [26]	2	✓	-	-	R/D	two-part tariff
Li et al. [25]	2	✓	-	-	R/D	-
Liu et al. [17]	2	-	-	-	R	-
Jian et al. [33]	2	-	-	-	R	profit-sharing
Wang et al. [34]	2	-	-	-	R	-
Wang et al. [16]	2	-	EX	-	R	sharing of cost and subsidy
Shi et al. [35]	2	-	-	-	R	sharing of cost and profit
Han et al. [36]	2	-	-	-	R	sharing of cost and profit
This study	3	✓	EN	✓	R/D	two-part tariff

EX = exogenous, EN = endogenous, R = recognition, D = disregard, SW = social welfare, FC = fairness concerns.

According to the research gap illustrated in Table 1, the innovations from our study are shown below:

(1) Solving the firms' pricing decisions and different attitudes towards fairness issues in the government-led CLSC;
(2) A two-part tariff contract is designed to coordinate the three-echelon CLSC with fairness concerns;
(3) Analyzing the impacts of waste pollution and fairness issues on economic benefits and social welfare.

3. Model Description and Assumptions

3.1. Problem Description

This study constructs a government-led CLSC that contains a government, a manufacturer, and a fairness-concerned retailer. As shown in Figure 1, the manufacturer offers products and recycles the waste products by the retailer. The government provides the manufacturer with subsidies to support remanufacturing. There is a Stackelberg game dominated by the government among the three players. The following is a description of the event's sequence. First, the government decides on the unit remanufacturing subsidy. Next, the manufacturer specifies the wholesale price and the unit purchasing price of the waste for the retailer. Finally, the retailer decides on the sales price and the unit recovery price of waste products for the customers. Because the retailer is a weak party in the game and pays a cost for recycling the used products, it could have fairness concerns in relation to the allocation of channel benefits, but the manufacturer can decide whether to recognize the concerned behavior.

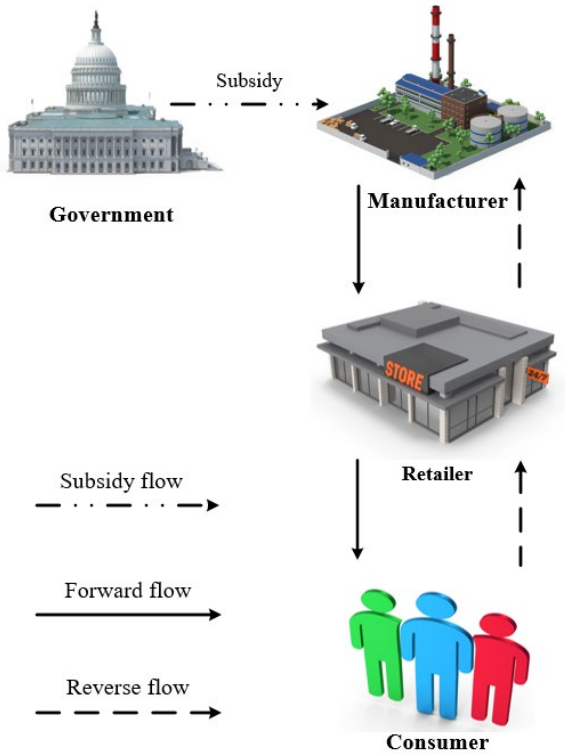


Figure 1. The government-led CLSC.

To study the fairness issue of the retailer and the manufacturer's attitude toward it in the game of CLSC under the leadership of the government, as well as to examine the optimal solutions of each participant in the game under different scenarios, we consider four possible models (model N, RY, RN, and C). In model N, the retailer does not have fairness concerns; in model RY, the retailer is fairness-concerned, and the manufacturer recognizes it when making pricing decisions; in model RN, the retailer's fairness concern

behavior is ignored by the manufacturer; and model C is a centralized model in which the two firms collaborate to make decisions together.

3.2. Notations

The indices, parameters, and variables are provided in Table 2.

Table 2. Notations and definitions.

Notations	Definitions
Indices:	
i	Subscript index of projects $i \in \{m, r, sc\}$, denotes the manufacturer, the retailer, and the supply chain
j	Superscript index of scenarios $j \in \{N, RY, RN, C, T\}$, denotes the models N, RY, RN, and C, and the coordination scenario T
Parameters:	
a	Initial market scale
β	The price elasticity coefficient of a product
c_m	Unit production cost of using new materials
c_r	Unit production cost of using a waste product
Δ	Unit saving through remanufacturing
θ	Consumer's environmental awareness
m	The consumer sensitivity of the recycling price
ε	Environmental burden of an unrecycled product
λ	The fairness concern coefficient
Decision variables:	
p	The retail price
w	The wholesale price
p_c	Unit recycling price paid to consumers
b	Unit transfer price paid to the retailer
s	Unit remanufacturing subsidy
Outcome variables:	
D	The market demand
Q	The production of products
Q_r	The recycling volume
π	The profit function
U_r	The fairness-concerned retailer's utility
SW	The social welfare
$F_{\min}$, $F_{\max}$	The negotiation bottom line and upper bound of enterprises

3.3. Assumptions

The basic assumptions are summarized as follows to facilitate the study:

1. Products made of waste products and products made from new materials are homogeneous. All recycled products are processed into new goods, there is no loss during remanufacturing, and all waste products recycled by the retailer will be converted into new products [1,24].
2. The demand function is assumed as follows: $D = a - \beta p$. Here, β stands for price elasticity of products, a stands for the market potential size, and p is the sales price. As the demand size is determined, the production of products Q is equal to the demand [13,24].
3. Producing products using new materials has a higher unit cost than producing with waste products, $c_m > c_r$. Δ is denoted as the unit cost saved from remanufacturing, and $\Delta = c_m - c_r$ [11,13,24]. The market size is large enough to ensure profitable sales of the product, and it is assumed that $a - \beta c_m > 0$ [24].
4. The retailer's recycling volume Q_r is a linear function of the recycling price paid to the consumers: $\theta + mp_c$ [13,26,37], where θ is the amount of used products that the retailer can obtain without providing recycling fees, and m stands for the consumer sensitivity to the recycling price.

5. In order to encourage recycling and remanufacturing activities, the government provides the manufacturer with a unit remanufacturing subsidy [11,24].
6. Maximizing social welfare is the purpose of the remanufacturing subsidy, and we denote social welfare as the sum of the revenues of enterprises, consumer surplus CS, subsidy expenditure F, and the environmental impact of products that have not been recycled [38]. The social welfare function is $SW = \pi_r + \pi_m + CS - F - \varepsilon(Q - Q_r)$, where ε is the environmental damage per unit of used unrecycled product. CS represents the distinction between the price that consumers actually pay in the market and the highest price they are willing to pay for a specific number of products. The function is $CS = \frac{Q^2}{2\beta}$ [20].

4. Model Development and Solution

This section attempts to derive and analyze the optimal decisions of different models (N, RY, RN, and C).

4.1. Model N

In this scenario, the goal of both enterprises in the supply chain is to maximize their profits. The unit subsidy is decided by the government first, then the manufacturer decides the wholesale price and the unit transfer price for the waste product, and finally the retailer sets the market price and the unit recycling price of the product.

The profit functions of the retailer and the manufacturer are as follows:

$$\pi_r = (a - \beta p)(p - w) + (b - p_c)(\theta + mp_c) \tag{1}$$

$$\pi_m = (a - \beta p)(w - c_m) + (\Delta - b + s)(\theta + mp_c). \tag{2}$$

The objective function of government is as follows:

$$SW = (a - \beta p)(p - c_m) + (\Delta - p_c)(\theta + mp_c) + \frac{(a - \beta p)^2}{2\beta} - \varepsilon(a - \beta p - (\theta + mp_c)) \tag{3}$$

Using backward induction, we derive the optimal solutions of the three players as follows:

$$p^{N*} = \frac{3a + \beta c_m}{4\beta}$$

$$p_c^{N*} = \frac{\Delta}{2} + \frac{\varepsilon}{2} - \frac{\theta}{2m}$$

$$b^{N*} = \Delta + \varepsilon$$

$$w^{N*} = \frac{a}{2\beta} + \frac{c_m}{2}$$

$$s^{N*} = \Delta + \frac{\theta}{m} + 2\varepsilon$$

$$\pi_r^{N*} = \frac{(a - \beta c_m)^2}{16\beta} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{m}{4}$$

$$\pi_m^{N*} = \frac{(a - \beta c_m)^2}{8\beta} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{m}{2}$$

$$\pi_{sc}^{N*} = \frac{3(a - \beta c_m)^2}{16\beta} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{3m}{4}$$

$$SW^{N*} = \frac{7(a-\beta c_m)^2}{32\beta} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{m}{4} - \frac{\varepsilon(a-\beta c_m)}{4}$$

4.2. Model RY

In this case, the retailer is concerned about the income gap with its upstream enterprise; its goal is to maximize its fairness utility when making decisions. Based on the existing studies [39,40], the retailer's utility function is formulated as follows:

$$U_r = \pi_r - \lambda(\pi_m - \pi_r) \tag{4}$$

In Equation (4), $\lambda \geq 0$ stands for the coefficient of fairness concern. The greater the coefficient, the more the retailer cares about fairness. In other words, λ represents the degree of fairness concern about the income distribution between two firms. If π_m is higher than π_r, U_r decreases in λ. When π_m is less than π_r, U_r would increase in λ. The objective functions of government and manufacturer are consistent with model N.

In model RY, as an enterprise that makes decisions ahead of its subordinate retailers, the manufacturer takes the retailer's utility as a reference when making decisions. The sequence of the decision-making process is the same as before, and we derive the optimal decisions by backward induction:

$$p^{RY*} = \frac{3a + \beta c_m}{4\beta}$$

$$p_c^{RY*} = \frac{\Delta}{2} - \frac{\theta}{2m} + \frac{\varepsilon}{2}$$

$$b^{RY*} = \frac{(1+3\lambda)\Delta}{(1+2\lambda)} + \frac{\lambda\theta}{(1+2\lambda)m} + \frac{(1+3\lambda)}{(1+2\lambda)}\varepsilon$$

$$w^{RY*} = \frac{(1+\lambda)a}{2\beta(1+2\lambda)} + \frac{(1+3\lambda)c_m}{2(1+2\lambda)}$$

$$s^{RY*} = \Delta + \frac{\theta}{m} + 2\varepsilon$$

$$\pi_r^{RY*} = \frac{(1+4\lambda)(a-\beta c_m)^2}{16\beta(1+2\lambda)} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{(1+4\lambda)m}{4(1+2\lambda)}$$

$$\pi_m^{RY*} = \frac{(1+\lambda)(a-\beta c_m)^2}{8\beta(1+2\lambda)} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{(1+\lambda)m}{2(1+2\lambda)}$$

$$\pi_{sc}^{RY*} = \frac{3(a-\beta c_m)^2}{16\beta} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{3m}{4}$$

$$SW^{RY*} = \frac{7(a-\beta c_m)^2}{32\beta} + \left(\frac{\theta}{m} + \Delta + \varepsilon\right)^2 \frac{m}{4} - \frac{\varepsilon(a-\beta c_m)}{4}$$

$$U_r^{RY*} = \frac{(1+\lambda)(a-\beta c_m)^2}{16\beta} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{m(1+\lambda)}{4}$$

4.3. Model RN

In model RN, the retailer still retains fairness concerns about the distribution of benefits between two enterprises, but the manufacturer does not respond to it and takes the retailer's profits as the reference for decision-making rather than fairness utility. The government

considers the enterprises' different attitudes towards fairness when setting the optimal subsidy. We can derive the optimal decisions as follows:

$$p^{RN*} = \frac{(3+4\lambda)a + \beta c_m}{4(1+\lambda)\beta}$$

$$p_c^{RN*} = \frac{\Delta}{2} - \frac{\theta}{2m} + \frac{\varepsilon}{2}$$

$$b^{RN*} = (1+\lambda)\Delta + \frac{\lambda\theta}{m} + (1+\lambda)\varepsilon$$

$$w^{RN*} = \frac{a}{2\beta} + \frac{c_m}{2}$$

$$s^{RN*} = (1+2\lambda)\left(\Delta + \frac{\theta}{m}\right) + 2(1+\lambda)\varepsilon$$

$$\pi_r^{RN*} = \frac{(1+2\lambda)(a-\beta c_m)^2}{16\beta(1+\lambda)^2} + \left(\frac{\theta}{m} + \Delta + \varepsilon\right)^2 \frac{(1+2\lambda)m}{4}$$

$$\pi_m^{RN*} = \frac{(a-\beta c_m)^2}{8\beta(1+\lambda)} + \left(\frac{\theta}{m} + \varepsilon + \Delta\right)^2 \frac{(1+\lambda)m}{2}$$

$$\pi_{sc}^{RN*} = \frac{(3+4\lambda)(a-\beta c_m)^2}{16\beta(1+\lambda)^2} + \left(\frac{\theta}{m} + \varepsilon + \Delta\right)^2 \frac{(3+4\lambda)m}{4}$$

$$SW^{RN*} = \frac{(7+8\lambda)(a-\beta c_m)^2}{32\beta(1+\lambda)^2} + \left(\frac{\theta}{m} + \Delta + \varepsilon\right)^2 \frac{m}{4} - \frac{\varepsilon(a-\beta c_m)}{4(1+\lambda)}$$

$$U_r^{RN*} = \frac{(a-\beta c_m)^2}{16\beta(1+\lambda)} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{m(1+\lambda)}{4}$$

4.4. Model C

In this model, the two enterprises form an alliance and make decisions collectively to increase the overall profits, and then the centralized model is used. The alliance's profit function is formulated as follows:

$$\pi_{sc}(p, p_c) = (a - \beta p)(p - c_m) + (\Delta - p_c + s)(\theta + m p_c) \tag{5}$$

The game's order is that the government determines the unit remanufacturing subsidy first, and then the alliance sets the market price and the recycling price. We derive the optimal decisions by backward induction:

$$p^{C*} = \frac{a + \beta c_m}{2\beta}$$

$$p_c^{C*} = \frac{\Delta}{2} - \frac{\theta}{2m} + \frac{\varepsilon}{2}$$

$$s^{C*} = \varepsilon$$

$$\pi_{sc}^{C*} = \frac{(a-\beta c_m)^2}{4\beta} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{m}{4}$$

$$SW^{C*} = \frac{3(a-\beta c_m)^2}{8\beta} + \left(\frac{\theta}{m} + \Delta + \varepsilon\right)^2 \frac{m}{4} - \varepsilon\frac{(a-c_m\beta)}{2}$$

4.5. Analysis of Equilibrium Results

We examine the influences of key parameters on optimal solutions and provide a comparative analysis of models.

Proposition 1. *For all scenarios, p^*, w^* are independent of ε, p_c^*, b^*, s^*, π_r^*, π_m^*, π_{sc}^*, U_r^{RY*} and U_r^{RN*} increases with ε. SW^{N*} and SW^{C*} decreases with ε; SW^{RN*} increases withε, when $\lambda > \lambda_{sw}^{RN}$, otherwise, it decreases with ε.*

Note: $\lambda_{sw}^{RN} = \frac{(a-\beta c_m)}{2m}\left(\varepsilon + \Delta + \frac{\theta}{m}\right)^{-1} - 1$.

From this proposition, we can see that the environmental cost of the waste product ε does not affect the pricing decisions of the two enterprises in forward logistics. With the increase in ε, the government increases subsidies to encourage recycling, so the recycling price, transfer prices of the waste, the retailer's fairness utility, and both enterprises' profits are improved. Social welfare is negatively correlated with ε, except when a relatively high λ is ignored by the manufacturer.

Proposition 2. *p^{RY*}, p_c^{RY*}, s^{RY*}, π_{sc}^{RY*} and SW^{RY*} are independent of λ; w^{RY*}, π_m^{RY*} decreases with λ; b^{RY*}, π_r^{RY*} and U_r^{RY*} increases with λ.*

Proposition 2 shows the influence of the retailer's fairness concerns on the manufacturer's response in the CLSC system. The manufacturer pays a greater transfer price for used products and lowers its wholesale price to deal with fairness issues, and this results in a decline in its profits while increasing the retailer's profits. The retailer's fairness utility increases with λ unless the fairness issue is ignored when the unit waste pollution is high. In addition, we can infer that, as the manufacturer recognizes the fairness concerns in the second stage of the Stackelberg game, the government's subsidy decision in the first stage of the game and the pricing decisions of the retailer in the third stage are unrelated to λ. Therefore, this causes the sales price, the channel profits of the two enterprises, and the social welfare to be not affected by the fairness concern.

Proposition 3. *p_c^{RN*}, w^{RN*} are independent of λ; p^{RN*}, b^{RN*}, s^{RN*} increases with λ; π_r^{RN*}, π_m^{RN*}, π_{sc}^{RN*}, SW^{RN*} increase with λ, when $\varepsilon > \varepsilon_r^{RN}$, $\varepsilon > \varepsilon_m^{RN}$, $\varepsilon > \varepsilon_{sc}^{RN}$, $\varepsilon > \varepsilon_{sw}^{RN}$, respectively, otherwise, they decrease with λ; when $\varepsilon > \varepsilon_U$, U_r^{RN*} increases with λ, otherwise, it decreases with λ.*

Note: $\varepsilon_U = \sqrt{\frac{(a-\beta c_m)^2}{4\beta m(1+\lambda)^2}} - \left(\Delta + \frac{\theta}{m}\right)$, $\varepsilon_r^{RN} = \sqrt{\frac{\lambda(a-\beta c_m)^2}{4m\beta(1+\lambda)^3}} - \left(\frac{\theta}{m} + \Delta\right)$, $\varepsilon_m^{RN} = \sqrt{\frac{(a-\beta c_m)^2}{4m\beta(1+\lambda)^2}} - \left(\frac{\theta}{m} + \Delta\right)$, $\varepsilon_{sc}^{RN} = \sqrt{\frac{(1+2\lambda)(a-\beta c_m)^2}{8m\beta(1+\lambda)^3}} - \left(\frac{\theta}{m} + \Delta\right)$, $\varepsilon_{sw}^{RN} = \frac{(3+4\lambda)(a-\beta c_m)}{4\beta(1+\lambda)}$.

We can conclude from Proposition 3 that, without the manufacturer's response to the fairness issue, the government would consider providing more subsidy fees to address the increase in fairness concerns. Increasing subsidies would encourage the manufacturer to pay more transfer fees for used products. Finally, the retailer sets a higher sales price to gain more revenue because the manufacturer does not lower the wholesale price to respond to the concerns.

Moreover, when the pollution per unit of waste product is low, the increase in fairness concerns can raise the product's price and reduce sales, which harms the CLSC's economic benefits. When the used product has a high degree of environmental pollution, the rise in fairness concerns can bring more government subsidies and reduce the total pollution through low product sales, which makes the fairness concerns positively related to the enterprises' profits and social welfare. This also explains why the social welfare in Proposi-

tion 1 increases with e when a high λ is neglected, and the increase is brought about by the firm's profits. In addition, it is easy to find that the impact of e on the supply chain and social welfare is simultaneously influenced by the role of λ.

Proposition 4. *$\pi_r^{N*} < \pi_m^{N*}$; $\pi_r^{RY*} < \pi_m^{RY*}$, when $\lambda < \frac{1}{2}$; $\pi_r^{RY*} > \pi_m^{RY*}$, when $\lambda > \frac{1}{2}$; $\pi_m^{RN*} > \pi_r^{RN*}$.*

This proposition suggests that, in the scenario without fairness concerns, as a subsidiary enterprise, the retailer always receives less revenue than the manufacturer, which is in line with realistic expectations. Moreover, in the case where the manufacturer responds to the retailer's fairness concerns, the retailer will capture more of the channel profits as the degree of concern increases. This situation allows the retailer to outperform the manufacturer in terms of profits. In addition, the manufacturer can always make higher profits than the retailer in this three-stage game by ignoring the fairness issue.

Conclusion 1. *$p^{RN*} > p^{N*} = p^{RY*} > p^{C*}$, $p_c^{N*} = p_c^{RY*} = p_c^{RN*} = p_c^{C*}$, $b^{RN*} > b^{RY*} > b^{N*}$, $w^{N*} = w^{RN*} > w^{RY*}$, $s^{RN*} > s^{N*} = s^{RY*} > s^{C*}$.*

Conclusion 1 shows that, in the model RY, the manufacturer recognizes the retailer's concerns, lowers the wholesale price, and raises its transfer price to satisfy the follower. The impacts of the concerning behavior are absorbed perfectly by the manufacturer, which makes the sales price to customers and the optimal subsidy the same as in model N.

In contrast, when the manufacturer does not adjust the wholesale price to please the retailer in model RN, the concerns in the supply chain are jointly resolved by the government and the manufacturer. The government will raise subsidies to offer more revenue for enterprises, and the increase in subsidies directly stimulates the manufacturer to pay a higher transfer price to the downstream retailer. At the same time, the retailer will also increase the market price to receive more revenue from the forward logistics. Therefore, the fairness problem at this point is defused by the increases in s, p, and b.

As for model C, two enterprises set the lowest sales price to expand the sales and bring benefits for the overall profits, while the government only considers the environmental cost of waste products when making decisions. Therefore, the lowest unit subsidy is set.

In addition, the fairness concerns under the four models do not affect the recycling price, so their recycling volumes are the same.

Conclusion 2.

(1) $\pi_r^{RY*} > \pi_r^{N*}$, $\pi_m^{N*} > \pi_m^{RY*}$; when $\varepsilon > \varepsilon_1$, $\pi_r^{RN*} > \pi_r^{N*}$and $\pi_m^{RN*} > \pi_m^{RY*}$, otherwise, $\pi_r^{RN*} < \pi_r^{N*}$ and $\pi_m^{RN*} < \pi_m^{RY*}$; when $\varepsilon > \varepsilon_2$, $\pi_r^{RN*} > \pi_r^{RY*}$, otherwise, $\pi_r^{RN*} < \pi_r^{RY*}$; when $\varepsilon > \varepsilon_3$, $\pi_m^{RN*} > \pi_m^{N*}$, otherwise, $\pi_m^{RN*} < \pi_m^{N*}$.
(2) $\pi_{sc}^{N*} = \pi_{sc}^{RY*}$; when $\varepsilon > \varepsilon_{sc1}$, $\pi_{sc}^{RN*} > \pi_{sc}^{RY*}$, otherwise, $\pi_{sc}^{RN*} < \pi_{sc}^{RY*}$; when $\varepsilon > \varepsilon_{sc2}$, $\pi_{sc}^{C*} < \pi_{sc}^{RY*}$, otherwise, $\pi_{sc}^{C*} > \pi_{sc}^{RY*}$; when $\varepsilon > \varepsilon_{sc3}$, $\pi_{sc}^{C*} < \pi_{sc}^{RN*}$, otherwise, $\pi_{sc}^{C*} > \pi_{sc}^{RN*}$.
(3) $SW^{N*} = SW^{RY*}$; when $\varepsilon > \varepsilon_{s1}$, $SW^{RN*} > SW^{RY*}$, otherwise, $SW^{RN*} < SW^{RY*}$; when $\varepsilon > \varepsilon_{s2}$, $SW^{C*} < SW^{RY*}$, otherwise, $SW^{C*} > SW^{RY*}$; when $\varepsilon > \varepsilon_{s3}$, $SW^{C*} < SW^{RN*}$, otherwise, $SW^{C*} > SW^{RN*}$.

Note: $\varepsilon_1 = \sqrt{\frac{\lambda(a-\beta c_m)^2}{8\beta m(1+\lambda)^2}} - \left(\frac{\theta}{m} + \Delta\right)$, $\varepsilon_2 = \sqrt{\frac{(5\lambda+2+4\lambda^2)(a-\beta c_m)^2}{16m\beta\lambda(1+\lambda)^2}} - \left(\frac{\theta}{m} + \Delta\right)$, $\varepsilon_3 = \sqrt{\frac{(a-\beta c_m)^2}{4m\beta(1+\lambda)}} - \left(\frac{\theta}{m} + \Delta\right)$, $\varepsilon_{sc1} = \sqrt{\frac{(3\lambda+2)(a-\beta c_m)^2}{16m\beta(1+\lambda)^2}} - \left(\frac{\theta}{m} + \Delta\right)$, $\varepsilon_{sc2} = \sqrt{\frac{(a-\beta c_m)^2}{8m\beta}} - \left(\Delta + \frac{\theta}{m}\right)$, $\varepsilon_{sc3} = \sqrt{\frac{(1+2\lambda)(a-\beta c_m)^2}{8\beta m(1+\lambda)^2}} - \left(\frac{\theta}{m} + \Delta\right)$, $\varepsilon_{s1} = \frac{(7\lambda+6)(a-\beta c_m)}{8\beta(1+\lambda)}$, $\varepsilon_{s2} = \frac{5(a-\beta c_m)}{8\beta}$, $\varepsilon_{s3} = \frac{\left(5+12\lambda^2+16\lambda\right)(a-\beta c_m)}{8\beta(1+3\lambda+2\lambda^2)}$.

Conclusion 2(1) shows that, in the three decentralized models, when the manufacturer responds to the concerns, it leaves more channel profits to the downstream firm by adjusting

pricing. The concerns that influence the two firms' profits are related to ε when the manufacturer disregards concerned behavior. Moreover, as the unit environmental impact of a waste item is at a low level, the manufacturer may choose to consider fairness concerns. The condition for the manufacturer ignoring the fairness concerns is equivalent to that for the retailer to maintain fairness concerns even if the manufacturer does not respond; that is, $\varepsilon > \varepsilon_1$. Therefore, the retailer chooses to always maintain fairness concerns. When the environmental pollution of used products is rather substantial, the manufacturer ignores the fairness concerns, and both firms will gain more owing to the increased level of concerns at this point. In addition, we can find that λ and ε_1 are positively correlated, and the increase in λ can make the two enterprises more likely to form the model RN.

From Conclusion 2(2), we can conclude that the manufacturer's response to fairness concerns does not change the overall profits. When the pollution degree of used products is high, the model RY and the model RN will bring more benefits to the firms; otherwise, the benefits of model C will be higher. By comparing ε_1, ε_{sc2}, and ε_{sc3}, we know that when the pollution level and coefficient of fairness concern are relatively low, the two enterprises will form an alliance and make decisions together; when these two parameters are relatively high, the supply chain enterprises tend to use model RN rather than the joint decision-making scenario. In addition, as ε_{sc3} decreases with λ, it can be concluded that the two main characteristics are not conducive to coordination.

Conclusion 2(3) indicates that the manufacturer's response to fairness concerns does not affect SW. The gap in social welfare between different models is also linked to both λ and ε. From $\varepsilon_{s1} > \varepsilon_{s3} > \varepsilon_{s2}$, we know that when the pollution degree of the waste product is low, enterprises can achieve higher social welfare through centralized decision-making. With the rise in pollution degree, SW is relatively lower under the centralized situation and, when the unit pollution value increases to a certain extent, model RN will achieve the highest level of social welfare.

5. Coordination Mechanism

Based on the preceding analysis, we know that the centralized model provides CLSC with more economic benefits under certain circumstances. Therefore, it is necessary to design a coordinated method for decentralized modes to achieve the equilibrium of model C.

Inspired by the research of Bai et al. [41], we coordinate the two enterprises by developing a two-part tariff contract to realize Pareto improvements. The agreement stipulates that the manufacturer will receive a fixed fund F from the retailer while providing the retailer with a more attractive wholesale price and payment for waste transfer. The coordination of this contract can make the market price, recycling price, and unit subsidy of decentralized modes consistent with those of model C, that is, $p^T = p^{C*}$, $p_c^T = p_c^{C*}$, $s_c^T = s^{C*}$. First, we express the profit functions of enterprises and the retailer's fairness utility as below:

$$\pi_r^T = (a - \beta p)(p - w) + (b - p_c)(\theta + m p_c) - F \tag{6}$$

$$\pi_m^T = (a - \beta p)(w - c_m) + (\Delta - b + s)(\theta + m p_c) + F \tag{7}$$

$$U_r^T = \pi_r - \lambda(\pi_m - \pi_r) = (1 + \lambda)\pi_r - \lambda \pi_m \tag{8}$$

Solving Equation (8) with the conditions of the contract, Proposition 5 can be obtained.

Proposition 5. *Under the coordination of two-part tariff contracts, the Manufacturer's pricing, the enterprises' profits, and the retailer's utility under can be formulated as:*

$$w^T = c_m$$

$$b^T = \Delta + \varepsilon$$

$$\pi_r^T = \frac{(a-\beta c_m)^2}{4\beta} + \left(\frac{\theta}{m} + \Delta + \varepsilon\right)^2 \frac{m}{4} - F$$

$$\pi_m^T = F$$

$$U_r^T = \frac{(1+\lambda)(a-\beta c_m)^2}{4\beta} + \left(\frac{\theta}{m} + \Delta + \varepsilon\right)^2 \frac{(1+\lambda)m}{4} - (1+2\lambda)F$$

Proposition 5 indicates that the manufacturer provides the goods at cost and sets the waste transfer price equal to that of the fairness-neutral model. In the coordination scenario, the fixed fund F charged to the retailer is the only profit source for the manufacturer.

To guarantee that both enterprises agree to the terms of the contract, we analyze the following conditions: the two enterprises' profits and the utility of the retailer after the implementation of coordination are not less than those of the decentralized models, that is,

$$\begin{cases} U_r^T \geq U_r^{RY}, U_r^{RN} \\ \pi_r^T \geq \pi_r^{RY}, \pi_r^{RN} \\ \pi_m^T \geq \pi_m^{RY}, \pi_m^{RN} \end{cases}$$

We analyze the above conditions and obtain the following conclusion.

Proposition 6. *The enterprises in CLSC will accept the two-part tariff contract only if the fixed fee F satisfies the following conditions:*

$$\begin{cases} F_{\min}^{RY} \leq F \leq F_{\max}^{RY} 0 < \varepsilon < \varepsilon_1 \\ F_{\min}^{RN} \leq F \leq F_{\max}^{RN} \varepsilon_1 < \varepsilon < \varepsilon_{sc3} \end{cases}$$

Note: $F_{\min}^{RY} = \frac{(1+\lambda)(a-\beta c_m)^2}{8\beta(1+2\lambda)} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{(1+\lambda)m}{2(1+2\lambda)}$, $F_{\max}^{RY} = \frac{(3+3\lambda)(a-\beta c_m)^2}{16\beta(1+2\lambda)}$,
$F_{\min}^{RN} = \frac{(a-\beta c_m)^2}{8\beta(1+\lambda)} + \left(\frac{\theta}{m} + \varepsilon + \Delta\right)^2 \frac{(1+\lambda)m}{2}$, $F_{\max}^{RN} = \frac{\left(3+4\lambda^2+8\lambda\right)(a-\beta c_m)^2}{16\beta(1+\lambda)(1+2\lambda)}$.

Proposition 6 shows the range of F when the two enterprises accept the contract, and they are win–win through the coordination of model RY and model RN.

Proposition 7.

(1) *The lower bounds of the fixed fees $F_{\min}^{RY}$, $F_{\min}^{RN}$ are related positively with ε; $F_{\min}^{RY}$ is related negatively with λ, $F_{\min}^{RN}$ increase with λ, when $\varepsilon > \varepsilon_m^{RN}$, otherwise, it decreases with λ.*

(2) *The upper bounds of the fixed fees $F_{\max}^{RY}$, $F_{\max}^{RN}$ are independent of ε, and decrease with λ.*

Note: $\varepsilon_m^{RN} = \sqrt{\frac{(a-\beta c_m)^2}{4m\beta(1+\lambda)^2}} - \left(\frac{\theta}{m} + \Delta\right)$.

Proposition 7 shows the fixed fees' lower bounds $F_{\min}^{RY}$; $F_{\min}^{RN}$ increases with ε, because the manufacturer's benefits in model RY and model RN are related positively to ε, that is, the manufacturer needs to be allocated more benefits to meet its bottom line. As the manufacturer's income in model RY is negatively correlated with the fairness concern coefficient λ, its bottom line of cooperation will also decrease. In model RN, the manufacturer's profits and bottom line of cooperation increase with λ when $\varepsilon > \varepsilon_m^{RN}$ and decrease with λ when $\varepsilon < \varepsilon_m^{RN}$. Regarding the upper bounds of the fixed fees $F_{\max}^{RY}$ and $F_{\max}^{RN}$, the larger the λ, the lower the maximum amount of fixed fees that the retailer is willing to pay in the coordination mechanism because the gap of the retailer's utilities before and after coordination will decrease with the increase in λ in decentralized models.

6. Numerical Analysis

In this section, we offer numerical simulations to show the comparison results of the enterprises' profits and fairness-concerned retailer's utility for different models, and then analyze the choices of enterprises' attitudes toward fairness concerns. After that, we examine the feasible scope of the two-part tariff contract and its impacts on CLSC.

To meet the assumptions and particular conditions of our research, we set the parameters as shown in Table 3.

Table 3. Parameters of the case study.

Parameters	Value
a	200
β	8
c_m	19
c_r	17
Δ	2
θ	0.2
m	1.4

6.1. Comparing Models

To compare the enterprises' profits, the fairness-concerned utility of the retailer in each model under different parameter conditions is investigated. We set λ and ε to vary in the range of 0 to 0.8 and 0 to 5, respectively, and keep the other parameters constant. The comparison results are provided in Figure 2.

From Figure 2a,b, it is clear that the manufacturer tends to disregard the fairness concerns of the downstream retailer, except when the unit waste pollution ε is low while the level of fairness concerns is significant. In contrast, when the pollution degree is relatively low, the fairness-concerned behavior may be recognized. The increase in λ is beneficial to both enterprises when the unit pollution degree is high. Combining the manufacturer's attitude towards fairness-concerned behavior according to ε, the retailer can ensure its profit all the time by increasing the degree of concern and keep the manufacturer in a disadvantageous position when the environmental cost of the unit waste product is small. Figure 2c shows that the supply chain gains more overall profit when λ and ε are low. Figure 2d indicates that fairness concerns may have a negative effect on the retailer's utility when the manufacturer ignores it.

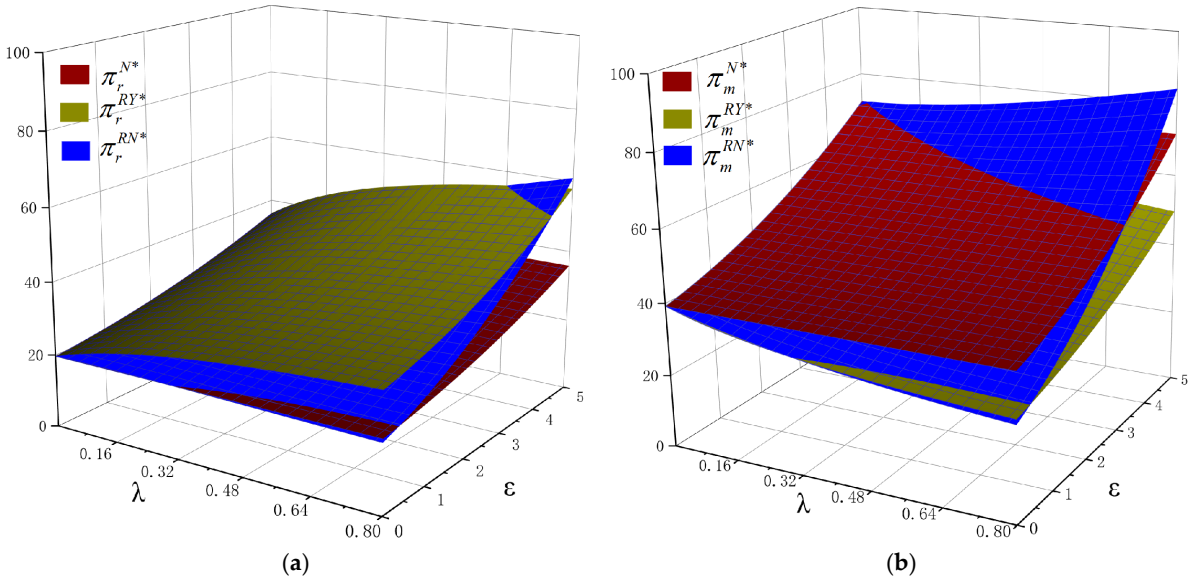
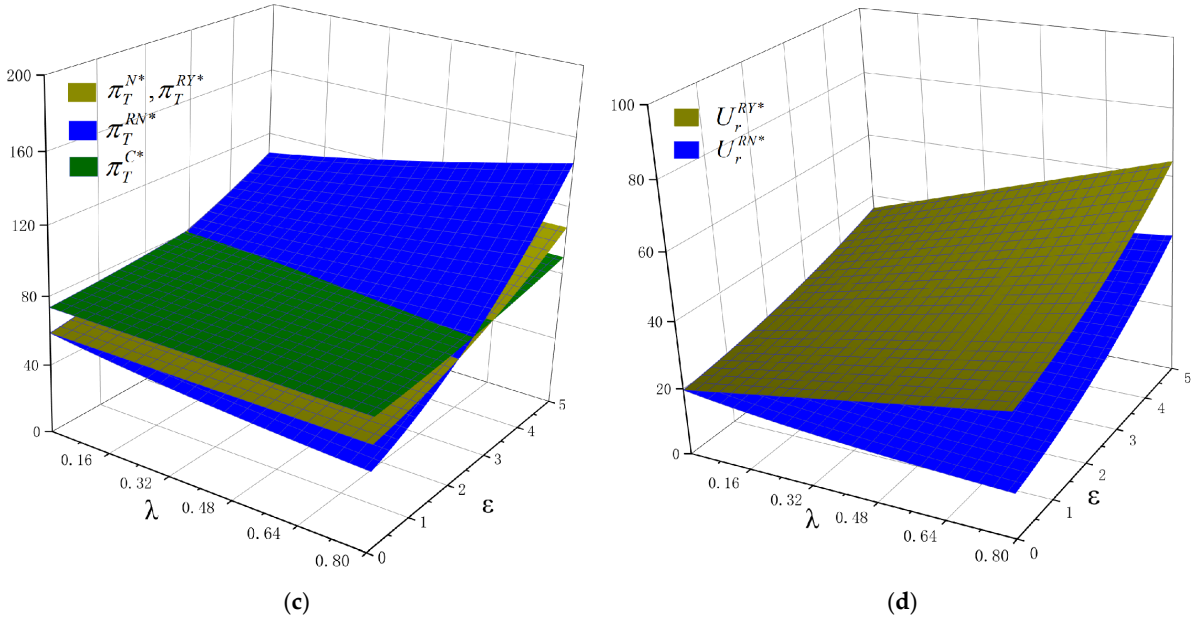


Figure 2. *Cont.*



(**c**) (**d**)

Figure 2. (**a**) The retailer's profit in different scenarios; (**b**) the manufacturer's profit in different scenarios; (**c**) overall profit in different scenarios; (**d**) the retailer's fairness utility in model RY and model RN.

6.2. The Impacts of Parameters on Firms' Attitudes toward Fairness Concerns and Coordination

Continuing with the parameter settings from the previous section, we clearly demonstrate the manufacturer's attitude towards fairness concerns and the profit conditions for centralized decision-making under different parameters (refer to Figures 3 and 4). From Figure 3, we can see that, in the decentralized scenarios, the rise in fairness concerns and unit environmental pollution of the waste product will cause the CLSC to tend to model RN. Figure 4 indicates that λ and ε are not conducive to business cooperation. Companies only consider centralized decision-making to make more profits when these two parameters are low.

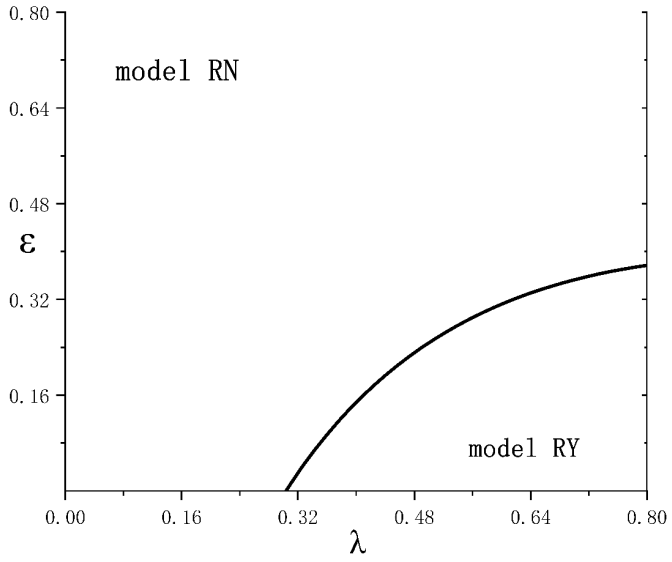


Figure 3. The manufacturer's choice of model under decentralized scenarios.

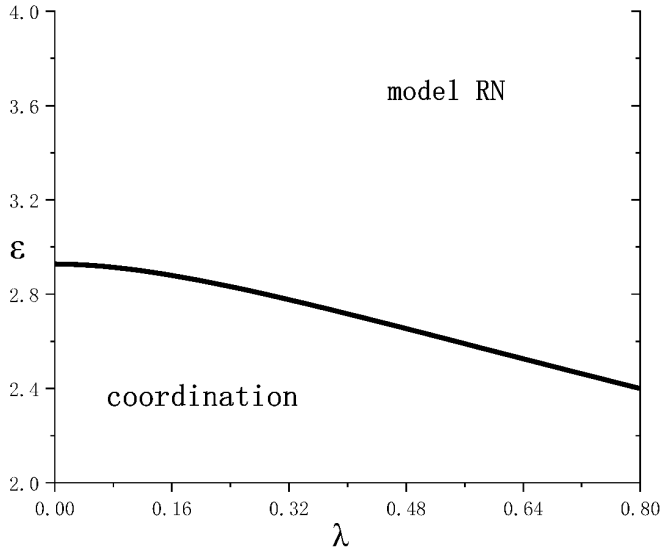
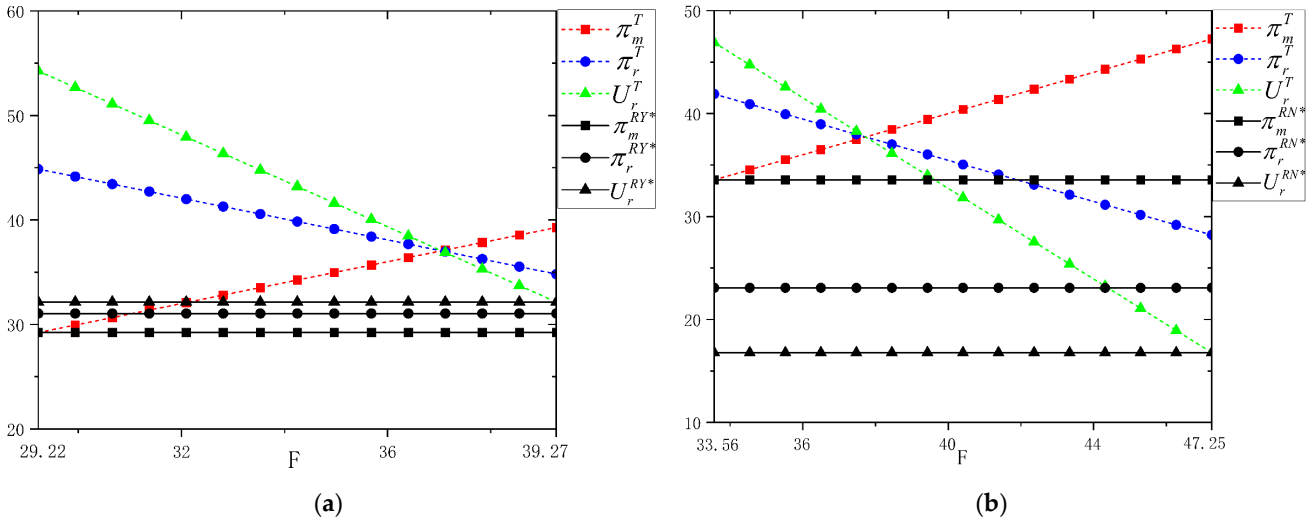


Figure 4. Total profit condition for enterprises to participate in coordination.

6.3. Analysis of the Coordination Process

Only when the channel profits of the centralized scenario exceed those of the two decentralized scenarios with fairness issues and the retailer's utility regarding fairness after coordination is not lower than before, then the two enterprises will consider accepting coordination. We separately set $\varepsilon = 0.3$ and $\lambda = 0.6$ for model RY and $\varepsilon = 1$ and $\lambda = 0.6$ for model RN, and keep the other parameters the same as before. The fixed fee from retailers to manufacturers is the key item for reaching cooperation. We demonstrate how F influences enterprises' profits and the retailer's fairness utility in Figure 5. This implies that, under certain parameter ranges, the two enterprises can come up with a win–win situation through this two-part tariff contract.



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

Figure 5. (**a**) Coordination role of F in model RY; (**b**) coordination role of F in model RN.

Next, Figure 6 shows how the upper bound and lower bound of F under model RY and model RN are impacted by the fairness concerns and waste product pollution. For model RY, we let $\varepsilon = 0.2$, $0 \le \lambda \le 0.8$ and set $\lambda = 0.6$, $0 \le \varepsilon \le 0.3$, then we can obtain Figure 6a,b; for model RN, we let $\varepsilon = 2$, $0 \le \lambda \le 0.8$ and $\lambda = 0.6$, $0.4 \le \varepsilon \le 2.56$, then Figure 6c,d are obtained. This setting is intended to meet the parameter conditions on model selection, as we have mentioned previously. Figure 6 indicates again that the

degree of fairness concern and the waste product pollution are adversely connected to the feasibility of the coordination. With the increase in these two parameters, the available interval of F for coordination is constantly being compressed. For the manufacturer, as ε rises, the government invests more money into the manufacturer, allowing it to obtain a higher negotiation bottom line, that is, $F_{\min}^{RY}$ and $F_{\min}^{RN}$ are positively associated with ε. In terms of the retailer, its fairness utility increases with λ in model RY and model RN, which leads to the continuous decline in the upper bounds $F_{\max}^{RY}$ and $F_{\max}^{RN}$. Although λ reduces the cooperation bottom line of the manufacturer in model RY, it also reduces the upper bounds of the fixed fees, because the retailer reaps increasing profits with the increase in λ when the manufacturer responds to its fairness concerns. For model RN, the compression of the fixed fees range caused by λ is shown in Figure 6c. The manufacturer receives more benefits if it chooses to ignore fairness concerns when ε is large, and the retailer also gains from the increase in λ at this moment, which also explains why $F_{\min}^{RN}$ in Figure 6c has a decreasing trend with λ when waste pollution is relatively high.

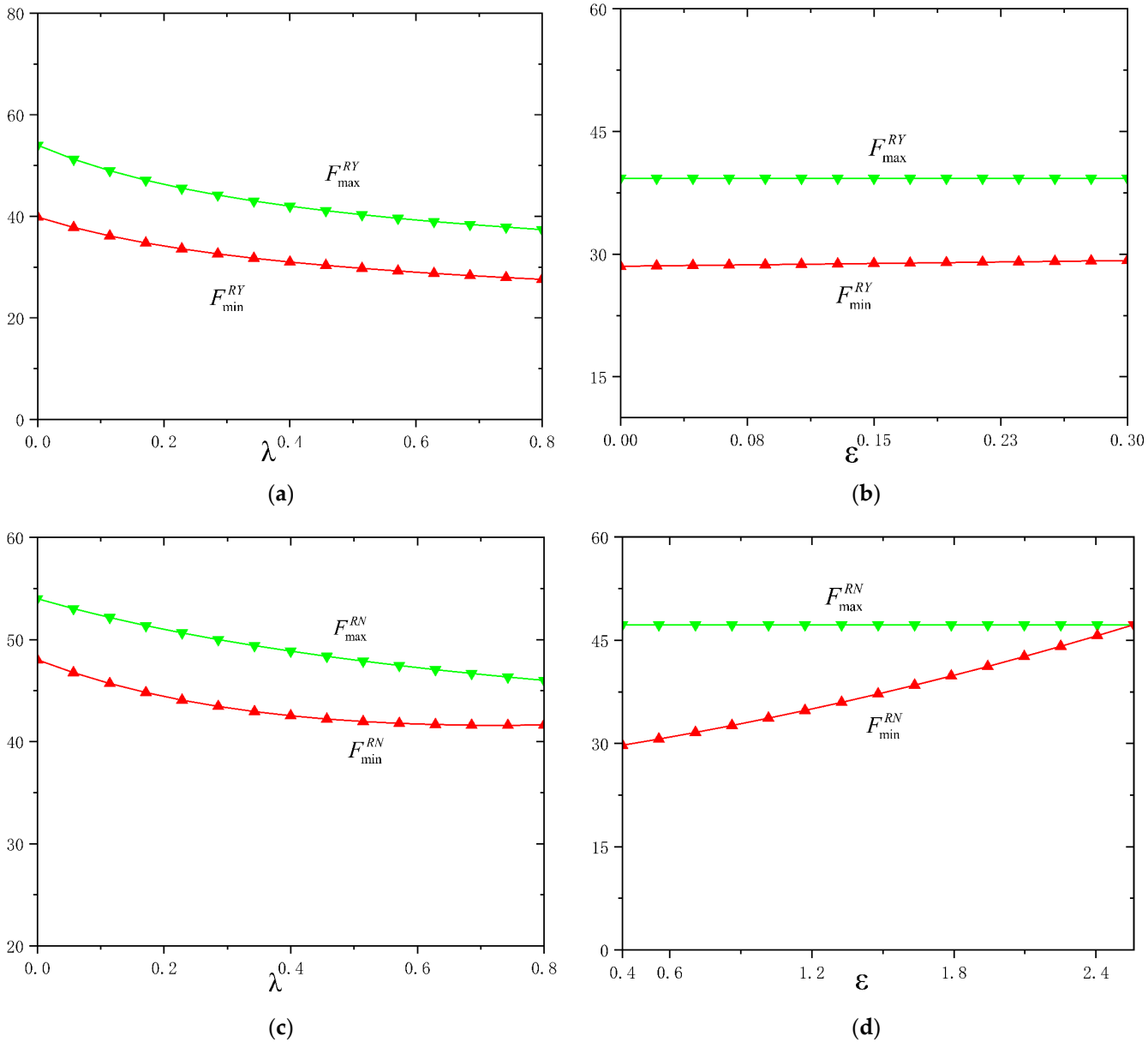


Figure 6. (**a**) Impact of λ on the interval of F in model RY; (**b**) impact of ε on the interval of F in model RY; (**c**) impact of λ on the interval of F in model RN; (**d**) impact of ε on the interval of F in model RN.

6.4. The Impact of Corporate Coordination on Social Welfare

Finally, our study demonstrates the effect of coordination on social welfare in Figure 7 by setting the parameter values to be consistent with Section 4.1.

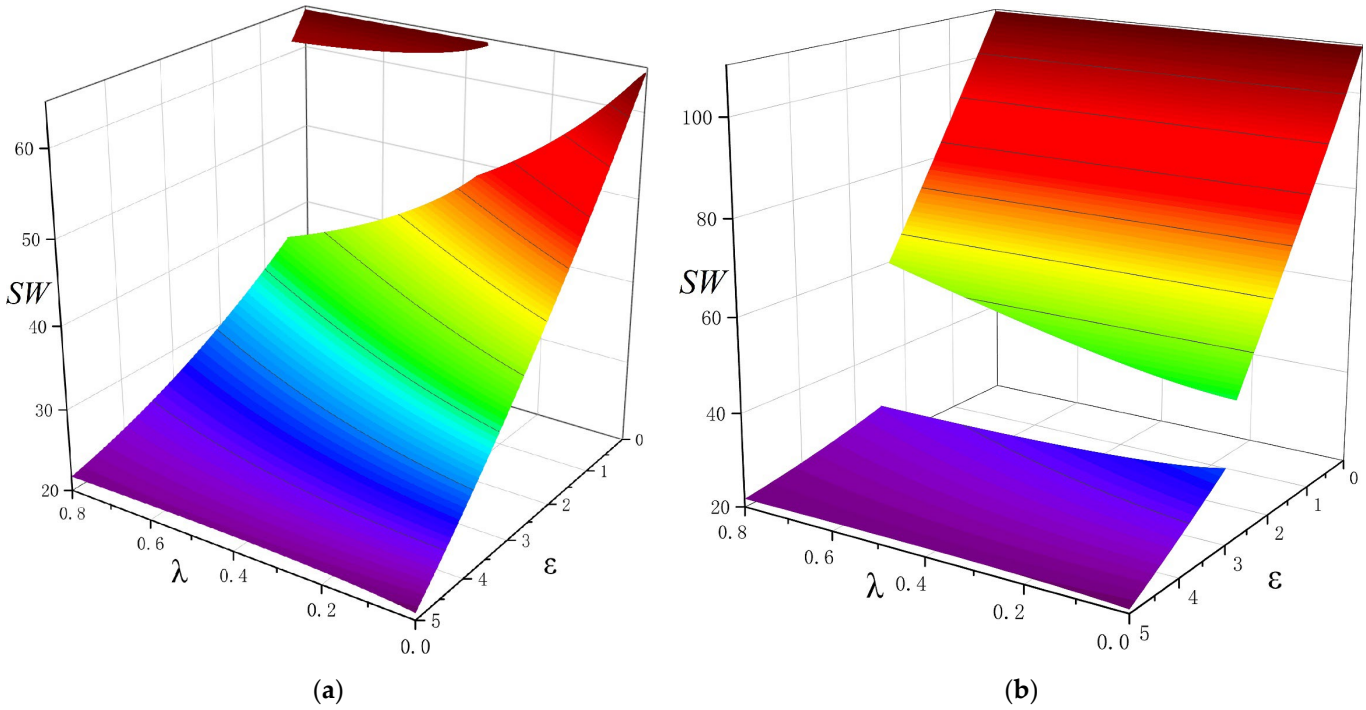


Figure 7. (**a**) Social welfare without the consideration of coordination; (**b**) social welfare with the consideration of coordination.

Figure 7 reflects the declining trend in social welfare with the increase in ε. According to Figure 7a, before considering coordination, the enterprises choose model RY when ε is low, and λ does not affect the social welfare in this situation. With the increase in ε, CLSC would enter model RN, and the increase in fairness concerns is partly advantageous for social welfare. According to Figure 7b, the supply chain with the consideration of coordination leads to a higher level of social welfare. When the pollution value reaches a certain degree, regardless of whether coordination is considered, the manufacturer will disregard the fairness concerns of the retailer. We can find that, when fairness concerns are ignored, social welfare is less affected by waste product pollution; this is because the manufacturer's neglect of fairness issues increases the government subsidy input.

7. Discussion and Managerial Insights

Based on the solving and comparison of models, we show the enterprises' attitudes towards fairness concerns under different levels of fairness concerns and unit waste pollution. Further, we provide a two-part tariff contract to coordinate two enterprises.

Considering the analysis of the proposed models, we provide managerial insights from the perspectives of enterprises and the government: (1) When the unit waste product pollution is low, the upstream and downstream enterprises of CLSC adopt centralized decision-making to improve overall revenue and coordinate the interests of both enterprises through the two-part tariff contract to address the fairness concerns of the downstream enterprises. Managers in enterprises need to accurately understand the fairness concerns and the pollution level of their unit waste product before making decisions to grasp the timing for forming alliances. (2) In the decentralized decision scenarios, the retailer can use fairness concerns to improve the revenue of CLSC. The manufacturer should only respond to the retailer's fairness concerns when the contamination level of the unit waste product is

relatively low and the retailer keeps a low degree of fairness concerns; otherwise, it can bring more subsidy revenue to the supply chain enterprises by ignoring fairness-concerned behavior. (3) As the manager of society, the government should strengthen communication with enterprises and encourage enterprises to coordinate. It is worth noting that although the government can promote remanufacturing and economic profits through high subsidies, the long-term high level of waste pollution and fairness issues among companies can place the government under severe financial pressure. We suggest that the government adopt subsidies while imposing requirements on the environmental performance of enterprises' products and strictly examining the authenticity of remanufacturing activities.

8. Conclusions

At present, waste utilization technology is gradually maturing and the phenomenon of government subsidies for environmental protection is more common. The fairness concerns caused by the power structure and subsidies need to be addressed in CLSC. Our research takes into account the optimal unit subsidy of the government and the retailer's fairness issues. Four decision models for CLSC were constructed: a decentralized fairness-neutral model; a decentralized model with a fairness-concerned retailer and a manufacturer who responds to the concerns; a decentralized model in which the manufacturer disregards the concerns; and a centralized model. This study investigates how fairness issues affect CLSC, government subsidy volume, and social welfare and further utilizes comparative analysis for the four models. A two-part tariff contract is created for enterprise coordination in decentralized scenarios. The following is a summary of the major findings of this study:

(1) The waste product pollution degree impacts government subsidies, while the amount of recycling is not affected by the retailer's fairness concerns. The government engages in more subsidized expenditure to deal with the fairness concerns ignored by the manufacturer (cf. Conclusion 1).
(2) In the decentralized models, when the unit waste pollution ε is low while the level of fairness concerns is significant, the manufacturer responds to the fairness concerns to mitigate the profit loss. With the rise in ε, the manufacturer will choose to ignore concerns, and the increase in the level of fairness concerns would provide more overall benefits to enterprises in this situation (cf. Figures 2 and 3, and Conclusion 2).
(3) As a subordinate enterprise, the retailer is always willing to maintain fairness concerns in response to the manufacturer's two kinds of attitudes in different scenarios (cf. Figure 2 and Conclusion 2).
(4) The enterprises can form a cooperative alliance through a two-part tariff contract when the degrees of unit waste pollution and fairness concerns are relatively low (cf. Figures 5 and 6), and the coordination contract provides higher social welfare to the government (cf. Figure 7).

Our study enriches the CLSC management research by combining the fair concern behavior of the subordinate enterprise, the upstream enterprise's attitude towards the fairness issue, and the optimal government subsidy in the CLSC game, and designing contracts to coordinate the enterprises. In addition, based on solving and comparing four game models under different fairness concern situations, this paper provides a basis for choosing pricing models for CLSC firms in the context of equity concerns and government subsidies, and it also provides a theoretical reference for the government to set optimal unit subsidies based on the treatment of fairness concerns.

This research has certain limitations that further studies might address. First, our research only studies government-led CLSC with a fairness-concerned retailer and a manufacturer, and future work could take an extension of our study into account, where the government-led CLSC consists of multiple retailers or manufacturers. Second, this study examines the influence of fairness concerns from a subordinate retailer. Future scholars can consider more situations where the upstream and downstream enterprises both have fairness concerns. Third, our research only studies one kind of government's optimal subsidy. Scholars can further consider the situation where the government formulates

optimal subsidies for different enterprises in the future, such as optimal subsidies to the retailer for selling remanufactured products.

In the future, we will further introduce additional types of concern behaviors, such as altruistic concerns and peer-induced fairness concerns in CLSC with government subsidies. Dual sales channel supply chains with an online channel and dual recovery channel supply chains will also be considered to investigate more complex concern behaviors. In addition, government policy on penalties and subsidies to enterprises will be considered in combination to provide more management policy references for the sustainable development of supply chains under corporate concerned behaviors.

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Appendix A

Solution procedure of model N:

Through Equation (1), a Hessian matrix for $\pi_r(p, p_c)$ can be obtained:

$$H = \begin{bmatrix} \partial^2\pi_r/\partial p^2 & \partial^2\pi_r/\partial p\partial p_c \\ \partial^2\pi_r/\partial p_c\partial p & \partial^2\pi_r/\partial {p_c}^2 \end{bmatrix} = \begin{bmatrix} -2\beta & 0 \\ 0 & -2m \end{bmatrix}$$

Because $-2\beta < 0$ and $4\beta m > 0$, the matrix is negative definite; $\pi_r(p, p_c)$ is concave in p and p_c. Solving equations $\frac{\partial\pi_r}{\partial p} = 0$ and $\frac{\partial\pi_r}{\partial p_c} = 0$ together, we obtain the retailer's optimal reactions:

$$p(w) = \frac{a}{2\beta} + \frac{w}{2} \tag{A1}$$

$$p_c(b) = \frac{b}{2} - \frac{\theta}{2m} \tag{A2}$$

Substituting Equations (A1) and (A2) into Equation (2), we obtain

$$\pi_m^N(w, b) = \left(\frac{a}{2} - \beta\frac{w}{2}\right)(w - c_m) + (\Delta - b + s)\left(\theta + m\frac{b}{2} - \frac{\theta}{2}\right)$$

The Hessian matrix of $\pi_m(w, b)$ is obtained:

$$H = \begin{bmatrix} \partial^2\pi_m/\partial w^2 & \partial^2\pi_m/\partial w\partial b \\ \partial^2\pi_m/\partial b\partial w & \partial^2\pi_m/\partial b^2 \end{bmatrix} = \begin{bmatrix} -\beta & 0 \\ 0 & -m \end{bmatrix}$$

Because $-\beta < 0$ and $\beta m > 0$, the matrix is negative definite; $\pi_m(w, b)$ has a maximum value under a given optimal subsidy. Solving $\frac{\partial \pi_m}{\partial w} = 0$ and $\frac{\partial \pi_m}{\partial b} = 0$ together, we obtain the optimal reactions of the manufacturer as below:

$$w^{N*} = \frac{a}{2\beta} + \frac{c_m}{2} \tag{A3}$$

$$b^N(s) = \frac{\Delta}{2} + \frac{s}{2} - \frac{\theta}{2m} \tag{A4}$$

Substituting Equations (A3) and (A4) into Equations (A1) and (A2), we obtain the following:

$$p^{N*} = \frac{3a}{4\beta} + \frac{c_m}{4} \tag{A5}$$

$$p_c^N(s) = \frac{1}{4}\Delta + \frac{1}{4}s - \frac{3\theta}{4m} \tag{A6}$$

Substituting Equations (A5) and (A6) into Equation (3), we obtain the following:

$$SW^N(s) = \frac{(a-\beta c_m)}{4}\left(\frac{3a}{4\beta} + \frac{c_m}{4} - \frac{4c_m}{4}\right) + \left(\Delta - \left(\frac{1}{4}\Delta + \frac{1}{4}s - \frac{3\theta}{4m}\right)\right)\left(\frac{\theta}{4} + \frac{1}{4}m\Delta + \frac{1}{4}ms\right) + \frac{(a-\beta c_m)^2}{32\beta} - \varepsilon\left(\frac{a-\beta c_m}{4} - \left(\frac{\theta}{4} + \frac{1}{4}m\Delta + \frac{1}{4}ms\right)\right)$$

Because $\frac{\partial^2 SW^N}{\partial s^2} = -\frac{m}{8} < 0$, SW^N is concave in s. Solving $\frac{\partial SW^N}{\partial s} = 0$, the optimal subsidy is $s^{N*} = \Delta + \frac{\theta}{m} + 2\varepsilon$. Substituting s^{N*} into Equations (A6) and (A4), we obtain the following:

$$p_c^{N*} = \frac{\Delta}{2} + \frac{\varepsilon}{2} - \frac{\theta}{2m},\ b^{N*} = \Delta + \varepsilon$$

Furthermore, the optimal profits and social welfare can be obtained.

Solution procedure of model RY:

Through Equation (4), the Hessian matrix of $U_r(p, p_c)$ is obtained:

$$H = \begin{bmatrix} \partial^2 U_r/\partial p^2 & \partial^2 U_r/\partial p \partial p_c \\ \partial^2 U_r/\partial p_c \partial p & \partial^2 U_r/\partial {p_c}^2 \end{bmatrix} = \begin{bmatrix} -2(1+\lambda)\beta & 0 \\ 0 & -2(1+\lambda)m \end{bmatrix}$$

Because $-2(1+\lambda)\beta < 0$ and $4(1+\lambda)^2\beta m > 0$, $U_r(p, p_c)$ is concave in p and p_c. Solving $\frac{\partial U_r}{\partial p} = 0$ and $\frac{\partial U_r}{\partial p_c} = 0$, we obtain the retailer's optimal reactions:

$$p(w) = \frac{a}{2\beta} - \frac{\lambda c_m}{2(1+\lambda)} + \frac{(1+2\lambda)}{2(1+\lambda)}w \tag{A7}$$

$$p_c(b, s) = \frac{(1+2\lambda)b}{2(1+\lambda)} - \frac{\theta}{2m} - \frac{\lambda\Delta}{2(1+\lambda)} - \frac{\lambda}{2(1+\lambda)}s \tag{A8}$$

Substituting Equations (A7) and (A8) into Equation (2), we obtain the following:

$$\pi_m^{RY}(w, b) = \left(a - \beta\left(\frac{a}{2\beta} - \frac{\lambda c_m}{2(1+\lambda)} + \frac{(1+2\lambda)}{2(1+\lambda)}w\right)\right)(w - c_m) + (\Delta - b + s)\left(\theta + m\left(\frac{(1+2\lambda)b}{2(1+\lambda)} - \frac{\theta}{2m} - \frac{\lambda\Delta}{2(1+\lambda)} - \frac{\lambda}{2(1+\lambda)}s\right)\right)$$

The Hessian matrix of $\pi_m^{RY}(w, b)$ is obtained:

$$H = \begin{bmatrix} \partial^2 \pi_m^{RY}/\partial w^2 & \partial^2 \pi_m^{RY}/\partial w \partial b \\ \partial^2 \pi_m^{RY}/\partial b \partial w & \partial^2 \pi_m^{RY}/\partial b^2 \end{bmatrix} = \begin{bmatrix} -\frac{\beta(1+2\lambda)}{(1+\lambda)} & 0 \\ 0 & -\frac{(1+2\lambda)m}{(1+\lambda)} \end{bmatrix}$$

Because $-\frac{\beta(1+2\lambda)}{(1+\lambda)} < 0$ and $\frac{\beta m(1+2\lambda)^2}{(1+\lambda)^2} > 0$, this matrix is negative definite; $\pi_m(w,b)$ is concave in w and b. Solving $\frac{\partial \pi_m^{RY}}{\partial w} = 0$ and $\frac{\partial \pi_m^{RY}}{\partial b} = 0$, the following equations can be obtained:

$$w^{RY*} = \frac{(1+\lambda)a}{2\beta(1+2\lambda)} + \frac{(1+3\lambda)c_m}{2(1+2\lambda)} \tag{A9}$$

$$b^{RY}(s) = \frac{(1+3\lambda)\Delta}{2(1+2\lambda)} - \frac{(1+\lambda)\theta}{2(1+2\lambda)m} + \frac{(1+3\lambda)s}{2(1+2\lambda)} \tag{A10}$$

Substituting Equations (A9) and (A10) into Equations (A7) and (A8), we obtain the following:

$$p^{RY*} = \frac{3a}{4\beta} + \frac{c_m}{4} \tag{A11}$$

$$p_c^{RY}(s) = \frac{1}{4}\Delta + \frac{1}{4}s - \frac{3\theta}{4m} \tag{A12}$$

Because $p^{RY*} = p^{N*}$ and $p_c^{RY}(s) = p_c^N(s)$, the government optimal subsidy of model RY is the same as that of model N:

$$s^{RY*} = \Delta + \frac{\theta}{m} + 2\varepsilon$$

Substituting s^{RY*} into Equations (A12) and (A10), we obtain the following:

$$p_c^{RY*} = \frac{\Delta}{2} + \frac{\varepsilon}{2} - \frac{\theta}{2m},\ b^{RY*} = \frac{(1+3\lambda)\Delta}{(1+2\lambda)} + \frac{\lambda\theta}{(1+2\lambda)m} + \frac{(1+3\lambda)}{(1+2\lambda)}\varepsilon$$

Then, we can derive the optimal profits, retailer's utility, and social welfare.

Solution procedure of model RN:

The optimal reactions of the retailer are the same as those of model RY and the manufacturer's reactions are the same as those of model N. Substituting Equations (A7) and (A8) into Equations (A3) and (A4), we obtain the following:

$$p^{RN*} = \frac{(3+4\lambda)a + \beta c_m}{4(1+\lambda)\beta} \tag{A13}$$

$$p_c^{RN}(s) = \frac{\Delta}{4(1+\lambda)} - \frac{(3+4\lambda)\theta}{4(1+\lambda)m} + \frac{s}{4(1+\lambda)} \tag{A14}$$

Substituting these two equations into Equation (3), we obtain the following:

$$\begin{aligned} SW = {} & \tfrac{a-\beta c_m}{4(1+\lambda)}\left(\tfrac{(3+4\lambda)a+\beta c_m}{4(1+\lambda)\beta} - c_m\right) + (\Delta - p_c)(\theta + mp_c) \\ & + \tfrac{(a-\beta c_m)^2}{32\beta(1+\lambda)^2} - \varepsilon\left(\tfrac{a-\beta c_m}{4(1+\lambda)} - (\theta + mp_c)\right) \end{aligned}$$

Because $\frac{\partial^2 SW^{RN}}{\partial s^2} = -\frac{m}{8(1+\lambda)^2} < 0$, SW^{RN} is concave in s. Solving $\frac{\partial SW^{RN}}{\partial s} = 0$, the optimal subsidy is as follows:

$$s^{RN*} = (1+2\lambda)\left(\Delta + \frac{\theta}{m}\right) + 2(1+\lambda)\varepsilon$$

Substituting s^{RN*} into Equations (A4) and (A14), we obtain the following:

$$p_c^{RN*} = \frac{\Delta}{2} + \frac{\varepsilon}{2} - \frac{\theta}{2m},\ b^{RN*} = \Delta + \varepsilon$$

Then, we can derive the profits of enterprises, the retailer's utility, and SW.

Solution procedure of model C

From Equation (A14), we formulate the Hessian matrix for π_{sc}:

$$H = \begin{bmatrix} \partial^2\pi_{sc}/\partial p^2 & \partial^2\pi_{sc}/\partial p\partial p_c \\ \partial^2\pi_{sc}/\partial p_c\partial p & \partial^2\pi_{sc}/\partial {p_c}^2 \end{bmatrix} = \begin{bmatrix} -2\beta & 0 \\ 0 & -2m \end{bmatrix}$$

Because $-2\beta < 0$ and $4\beta m > 0$, $\pi_T(p, p_c)$ has an optimal solution. By letting $\frac{\partial\pi_{sc}}{\partial p} = 0$ and $\frac{\partial\pi_{sc}}{\partial p_c} = 0$,

$$p^{C*} = \frac{a + c_m\beta}{2\beta},\ p_c^C(s) = \frac{\Delta}{2} - \frac{\theta}{2m} + \frac{s}{2}$$

Substituting p^{C*} and p_c^{C*} into Equation (3), we obtain the following:

$$SW^C = (a - \beta p)(p - c_m) + (\Delta - p_c)(\theta + mp_c) + \frac{(a - \beta p)^2}{2\beta} - \varepsilon(a - \beta p - (\theta + mp_c))$$

Because $\frac{\partial^2 SW^C}{\partial s^2} = -\frac{m}{2} < 0$, SW^C is concave in s. Solving $\frac{\partial SW^C}{\partial s} = 0$, the optimal subsidy is $s^{C*} = \varepsilon$. Substituting $s^{C*} = \varepsilon$ into $p_c^C(s)$, we obtain $p_c^{C*} = \frac{\Delta}{2} - \frac{\theta}{2m} + \frac{\varepsilon}{2}$.

Then, the optimal channel profits and social welfare can be obtained.

Proof of Proposition 1:

$$\frac{\partial p^{N*}}{\partial\varepsilon} = \frac{\partial p^{RY*}}{\partial\varepsilon} = \frac{\partial p^{RN*}}{\partial\varepsilon} = \frac{\partial p^{C*}}{\partial\varepsilon} = 0;\ \frac{\partial w^{N*}}{\partial\varepsilon} = \frac{\partial w^{RY*}}{\partial\varepsilon} = \frac{\partial w^{RN*}}{\partial\varepsilon} = 0;$$

$$\frac{\partial p_c^{N*}}{\partial\varepsilon} = \frac{\partial p_c^{RY*}}{\partial\varepsilon} = \frac{\partial p_c^{RN*}}{\partial\varepsilon} = \frac{\partial p_c^{C*}}{\partial\varepsilon} = \frac{1}{2} > 0;\ \frac{\partial b^{N*}}{\partial\varepsilon} = 1 > 0;\ \frac{\partial b^{RY*}}{\partial\varepsilon} = \frac{(1+3\lambda)}{(1+2\lambda)} > 0;$$

$$\frac{\partial b^{RN*}}{\partial\varepsilon} = (1 + \lambda) > 0;$$

$$\frac{\partial s^{N*}}{\partial\varepsilon} = \frac{\partial s^{RY*}}{\partial\varepsilon} = 2 > 0;\ \frac{\partial s^{RN*}}{\partial\varepsilon} = 2(1 + \lambda) > 0;$$

$$\frac{\partial\pi_r^{N*}}{\partial\varepsilon} = \frac{m}{2}\varepsilon + \frac{m}{2}\left(\Delta + \frac{\theta}{m}\right) > 0;\ \frac{\partial\pi_m^{N*}}{\partial\varepsilon} = m\varepsilon + m\left(\Delta + \frac{\theta}{m}\right) > 0;$$

$$\frac{\partial\pi_{sc}^{N*}}{\partial\varepsilon} = \frac{3m}{2}\varepsilon + \frac{3m}{2}\left(\Delta + \frac{\theta}{m}\right) > 0;$$

$$\frac{\partial SW^{N*}}{\partial\varepsilon} = \frac{\partial SW^{RY*}}{\partial\varepsilon} = \frac{m}{2}\varepsilon + \frac{m}{2}\left(\Delta + \frac{\theta}{m}\right) - \frac{(a - \beta c_m)}{4},$$

If $\frac{\partial SW^{N*}}{\partial\varepsilon} \geq 0$, we have the following:

$$\varepsilon \geq \frac{(a - \beta c_m)}{2m} - \left(\Delta + \frac{\theta}{m}\right), Q_r = \theta + mp_c^{N*} \geq Q = a - \beta p^{N*} = \frac{(a - \beta c_m)}{4},$$

Because we set the total quantity of waste goods in CLSC to not to exceed the market sales volume, when the recovered quantity reaches the product sales volume when the degree of pollution from discarded items rises, there are no pollutants in the environment, so we only consider the case of $\varepsilon \leq \frac{(a-\beta c_m)}{2m} - \left(\Delta + \frac{\theta}{m}\right)$.

When $\varepsilon \leq \frac{(a-\beta c_m)}{2m} - \left(\Delta + \frac{\theta}{m}\right)$, $\frac{\partial SW^{N*}}{\partial\varepsilon} = (m\varepsilon + m\Delta + \theta)/2 - \frac{(a-\beta c_m)}{4} \leq 0$; $\frac{\partial SW^{RN*}}{\partial\varepsilon} = \frac{m}{2}\varepsilon + \frac{m}{2}\left(\Delta + \frac{\theta}{m}\right) - \frac{(a-\beta c_m)}{4(1+\lambda)}$, and we know that only when $\frac{(a-\beta c_m)}{2m(1+\lambda)} - \left(\Delta + \frac{\theta}{m}\right) < \varepsilon < \frac{(a-\beta c_m)}{2m} - \left(\Delta + \frac{\theta}{m}\right)$, $\frac{\partial SW^{RN*}}{\partial\varepsilon} > 0$, that is, when $\frac{(a-\beta c_m)}{2m}\left(\varepsilon + \Delta + \frac{\theta}{m}\right)^{-1} - 1 < \lambda$, $\frac{\partial SW^{RN*}}{\partial\varepsilon} > 0$; $\frac{\partial SW^{C*}}{\partial\varepsilon} = \left(2\varepsilon + 2\left(\Delta + \frac{\theta}{m}\right)\right)\frac{m}{4} - \frac{(a-\beta c_m)}{2}$. Because ε will not exceed $\frac{(a-\beta c_m)}{2m} - \left(\Delta + \frac{\theta}{m}\right)$, we have $\frac{\partial SW^{C*}}{\partial\varepsilon} < 0$.

Similarly, firms' profits and retailer utility in the other models increase as a result of an increase in ε. □

Proof of Proposition 2:

In model RY, $\frac{\partial p_r^{RY*}}{\partial \lambda} = 0$; $\frac{\partial p_c^{RY*}}{\partial \lambda} = 0$; $\frac{\partial s^{RY*}}{\partial \lambda} = 0$; $\frac{\partial \pi_{sc}^{RY*}}{\partial \lambda} = 0$; $\frac{\partial SW^{RY*}}{\partial \lambda} = 0$; $\frac{\partial w^{RY*}}{\partial \lambda} = \frac{2\beta^2 c_m}{4\beta^2(1+2\lambda)^2} - \frac{2\beta a}{4\beta^2(1+2\lambda)^2} < 0$; $\frac{\partial \pi_m^{RY*}}{\partial \lambda} = -\frac{(a-\beta c_m)^2}{\beta(1+2\lambda)^2} - \frac{\left(\Delta+\frac{\theta}{m}+\varepsilon\right)^2 m}{2(1+2\lambda)^2} < 0$; $\frac{\partial b^{RY*}}{\partial \lambda} = \frac{(\Delta+\varepsilon)}{(1+2\lambda)^2} + \frac{m\theta}{(1+2\lambda)^2 m^2} > 0$; $\frac{\partial \pi_r^{RY*}}{\partial \lambda} = \frac{32\beta(a-\beta c_m)^2}{(16\beta(1+2\lambda))^2} + \frac{8\left(\Delta+\frac{\theta}{m}+\varepsilon\right)^2 m}{(4(1+2\lambda))^2} > 0$; $\frac{\partial U_r^{RY*}}{\partial \lambda} = \frac{(a-\beta c_m)^2}{16\beta} + \left(\Delta+\frac{\theta}{m}+\varepsilon\right)^2 \frac{m}{4} > 0$; □

Proof of Proposition 3:

In model RN, $\frac{\partial p_c^{RN*}}{\partial \lambda} = 0$, $\frac{\partial w^{RN*}}{\partial \lambda} = 0$, $\frac{\partial p^{RN*}}{\partial \lambda} = \frac{(a-\beta c_m)4}{(4(1+\lambda))^2\beta} > 0$, $\frac{\partial b^{RN*}}{\partial \lambda} = \Delta + \frac{\theta}{m} + \varepsilon > 0$, $\frac{\partial s^{RN*}}{\partial \lambda} = 2\left(\Delta + \frac{\theta}{m} + \varepsilon\right) > 0$;

$$\frac{\partial \pi_r^{RN*}}{\partial \lambda} = \left(\frac{\theta}{m} + \Delta + \varepsilon\right)^2 \frac{m}{2} - \frac{\lambda(a-\beta c_m)^2}{8\beta(1+\lambda)^3}, \text{ when } \varepsilon > \sqrt{\frac{\lambda(a-\beta c_m)^2}{4m\beta(1+\lambda)^3}} - \left(\frac{\theta}{m} + \Delta\right), \frac{\partial \pi_r^{RN*}}{\partial \lambda} > 0,$$

otherwise $\frac{\partial \pi_r^{RN*}}{\partial \lambda} < 0$;

$$\frac{\partial \pi_m^{RN*}}{\partial \lambda} = \left(\frac{\theta}{m} + \varepsilon + \Delta\right)^2 \frac{m}{2} - \frac{(a-\beta c_m)^2}{8\beta(1+\lambda)^2}, \text{ when } \varepsilon > \sqrt{\frac{(a-\beta c_m)^2}{4m\beta(1+\lambda)^2}} - \left(\frac{\theta}{m} + \Delta\right), \frac{\partial \pi_m^{RN*}}{\partial \lambda} > 0,$$

otherwise $\frac{\partial \pi_m^{RN*}}{\partial \lambda} < 0$;

$$\frac{\partial \pi_{sc}^{RN*}}{\partial \lambda} = \left(\frac{\theta}{m} + \varepsilon + \Delta\right)^2 m - \frac{(1+2\lambda)(a-\beta c_m)^2}{8\beta(1+\lambda)^3}, \text{ when } \varepsilon > \sqrt{\frac{(1+2\lambda)(a-\beta c_m)^2}{8m\beta(1+\lambda)^3}} - \left(\frac{\theta}{m} + \Delta\right),$$

$\frac{\partial \pi_{sc}^{RN*}}{\partial \lambda} > 0$, otherwise $\frac{\partial \pi_{sc}^{RN*}}{\partial \lambda} < 0$;

$$\frac{\partial SW^{RN*}}{\partial \lambda} = \frac{\varepsilon(a-\beta c_m)}{4(1+\lambda)^2} - \frac{(6+8\lambda)(a-\beta c_m)^2}{32\beta(1+\lambda)^3}, \text{ when } \varepsilon > \frac{(3+4\lambda)(a-\beta c_m)}{4\beta(1+\lambda)}, \frac{\partial SW^{RN*}}{\partial \lambda} > 0,$$

otherwise $\frac{\partial SW^{RN*}}{\partial \lambda} < 0$;

$$\frac{\partial U_r^{RN*}}{\partial \lambda} = -\frac{(a-\beta c_m)^2}{16\beta(1+\lambda)^2} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{m}{4},$$

when $\varepsilon > \varepsilon_U = \sqrt{\frac{(a-\beta c_m)^2}{4\beta m(1+\lambda)^2}} - \left(\Delta + \frac{\theta}{m}\right)$, $\frac{\partial U_r^{RN*}}{\partial \lambda} > 0$, otherwise there is a decrease with λ. □

Proof of Proposition 4:

$$\pi_m^{N*} - \pi_r^{N*} = \frac{(a-\beta c_m)^2}{16\beta} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{m}{4} > 0;$$

Because $\pi_m^{RY*} - \pi_r^{RY*} = \frac{(1-2\lambda)(a-\beta c_m)^2}{16\beta(1+2\lambda)} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{(1-2\lambda)m}{4(1+2\lambda)}$, when $\lambda < \frac{1}{2}$, $\pi_m^{RY*} - \pi_r^{RY*} > 0$, otherwise $\pi_m^{RY*} - \pi_r^{RY*} < 0$;

$$\pi_m^{RN*} - \pi_r^{RN*} = \frac{(a-\beta c_m)^2}{16\beta(1+\lambda)^2} + \left(\frac{\theta}{m} + \varepsilon + \Delta\right)^2 \frac{m}{4} > 0.$$

□

Proof of Conclusion 1:

$$p^{N*} = p^{RY*} = \frac{3a+\beta c_m}{4\beta},\ p^{N*} - p^{C*} = \frac{a-\beta c_m}{4\beta} > 0,\ p^{RN*} - p^{N*} = \frac{\lambda(a-\beta c_m)}{4(1+\lambda)\beta} > 0;$$

$$p_c^{N*} = p_c^{RY*} = p_c^{RN*} = p_c^{C*} = \frac{\Delta}{2} - \frac{\theta}{2m} + \frac{\varepsilon}{2};$$

$$b^{RN*} - b^{RY*} = \frac{2\lambda^2\Delta}{(1+2\lambda)} + \frac{2\lambda^2\theta}{(1+2\lambda)m} + \frac{2\lambda^2\varepsilon}{(1+2\lambda)} > 0;$$

$$b^{RY*} - b^{N*} = \frac{\lambda\Delta}{(1+2\lambda)} + \frac{\lambda\theta}{(1+2\lambda)m} + \frac{\lambda\varepsilon}{(1+2\lambda)} > 0;$$

$$w^{N*} = w^{RN*} = \frac{a}{2\beta} + \frac{c_m}{2},\ \frac{a}{2\beta} + \frac{c_m}{2} - w^{RY*} = \frac{\lambda(a-\beta c_m)}{2\beta(1+2\lambda)} > 0;$$

$$s^{N*} = s^{RY*} = \Delta + \frac{\theta}{m} + 2\varepsilon,\ s^{N*} - s^{C*} = \Delta + \frac{\theta}{m} + \varepsilon > 0,\ s^{RN*} - s^{N*} = 2\lambda\left(\Delta + \frac{\theta}{m} + \varepsilon\right) > 0;$$

□

Proof of Conclusion 2:

(1)

$$\pi_r^{RY*} - \pi_r^{N*} = \frac{\lambda(a-\beta c_m)^2}{8\beta(1+2\lambda)} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{\lambda m}{2(1+2\lambda)} > 0;$$

$$\pi_m^{N*} - \pi_m^{RY*} = \frac{\lambda(a-\beta c_m)^2}{8\beta(1+2\lambda)} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{\lambda m}{2(1+2\lambda)} > 0;$$

$\pi_r^{RN*} - \pi_r^{N*} = -\frac{\lambda^2(a-\beta c_m)^2}{16\beta(1+\lambda)^2} + \left(\frac{\theta}{m} + \Delta + \varepsilon\right)^2 \frac{\lambda m}{2}$, when $\varepsilon > \varepsilon_1$, $\pi_r^{RN*} - \pi_r^{N*} > 0$, otherwise $\pi_r^{RN*} - \pi_r^{N*} < 0$;

$$\pi_r^{RY*} - \pi_r^{RN*} = \frac{\left(5\lambda^2 + 2\lambda + 4\lambda^3\right)(a-\beta c_m)^2}{16\beta(1+2\lambda)(1+\lambda)^2} - \left(\frac{\theta}{m} + \Delta + \varepsilon\right)^2 \frac{\lambda^2 m}{(1+2\lambda)},$$

When $\varepsilon_2 > \varepsilon$, $\pi_r^{RY*} - \pi_r^{RN*} > 0$, otherwise $\pi_r^{RY*} - \pi_r^{RN*} < 0$;

$$\pi_m^{RN*} - \pi_m^{RY*} = \frac{(a-\beta c_m)^2}{8\beta(1+\lambda)} - \frac{(1+\lambda)(a-\beta c_m)^2}{8\beta(1+2\lambda)} + \left(\frac{\theta}{m} + \varepsilon + \Delta\right)^2 \frac{\lambda(1+\lambda)m}{(1+2\lambda)},$$

When $\varepsilon > \varepsilon_1$, $\pi_m^{RN*} - \pi_m^{RY*} > 0$, otherwise $\pi_m^{RN*} - \pi_m^{RY*} < 0$; $\pi_m^{RN*} - \pi_m^{N*} = \left(\frac{\theta}{m} + \varepsilon + \Delta\right)^2 \frac{\lambda m}{2} - \frac{\lambda(a-\beta c_m)^2}{8\beta(1+\lambda)}$, when $\varepsilon > \varepsilon_3$, $\pi_m^{RN*} - \pi_m^{N*} > 0$, otherwise $\pi_m^{RN*} - \pi_m^{N*} < 0$.

From the above, we can know that, in decentralized decision-making scenarios, because, when $\varepsilon > \varepsilon_1$, $\pi_r^{RN*} - \pi_r^{N*} > 0$ and $\pi_m^{RN*} - \pi_m^{RY*} > 0$, under this condition and the principle that the two enterprises pursue the maximization of profit, the retailer will choose to have fairness concerns, the manufacturer chooses to ignore it, and the CLSC system forms model RN; when $\varepsilon < \varepsilon_1$, the retailer does not maintain its fairness concerns and the system will form model N.

In addition, from $\frac{\partial\varepsilon_1}{\partial\lambda} = \frac{1}{2}\left(\frac{\lambda(a-\beta c_m)^2}{8\beta m(1+\lambda)^2}\right)^{-0.5} \frac{1-\lambda^2}{8\beta m(1+\lambda)^4}(a-\beta c_m)^2 \geq 0$, we know that ε_1 will increase with λ.

(2)

$$\pi_{sc}^{N*} = \pi_{sc}^{RY*} = \frac{3(a-\beta c_m)^2}{16\beta} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{3m}{4};$$

$$\pi_{sc}^{RY*} - \pi_{sc}^{RN*} = \frac{\left(3\lambda^2+2\lambda\right)(a-\beta c_m)^2}{16\beta(1+\lambda)^2} - \left(\frac{\theta}{m} + \varepsilon + \Delta\right)^2 \lambda m,$$

when $\varepsilon_{sc1} > \varepsilon$, $\pi_{sc}^{RY*} - \pi_{sc}^{RN*} > 0$, otherwise $\pi_{sc}^{RY*} - \pi_{sc}^{RN*} < 0$; $\pi_{sc}^{C*} - \pi_{sc}^{RY*} = \frac{(a-\beta c_m)^2}{16\beta} - \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{m}{2}$, when $\varepsilon_{sc2} > \varepsilon$, $\pi_{sc}^{C*} - \pi_{sc}^{RY*} > 0$, otherwise $\pi_{sc}^{C*} - \pi_{sc}^{RY*} < 0$; $\pi_{sc}^{C*} - \pi_{sc}^{RN*} = \frac{(1+2\lambda)^2(a-\beta c_m)^2}{16\beta(1+\lambda)^2} - \left(\frac{\theta}{m} + \varepsilon + \Delta\right)^2 \frac{(1+2\lambda)m}{2}$, when $\varepsilon_{sc3} > \varepsilon$, $\pi_{sc}^{C*} - \pi_{sc}^{RN*} > 0$, otherwise $\pi_{sc}^{C*} - \pi_{sc}^{RN*} < 0$.

Because, when $\varepsilon_{sc2} > \varepsilon$, $\pi_{sc}^{C*} - \pi_{sc}^{RY*} > 0$, we know that, under the condition of $\varepsilon_{sc2} > \varepsilon$, the channel profit brought by centralized decision-making exceeds that of model RY. Then, because, when $\varepsilon_{sc3} > \varepsilon$, $\pi_{sc}^{C*} - \pi_{sc}^{RN*} > 0$, we know that, under the condition of $\varepsilon_{sc3} > \varepsilon$, the channel profit brought by centralized decision-making exceeds that of model RN.

According to the above analysis, in the decentralized scenarios, when $\varepsilon > \varepsilon_1$, the CLSC forms model RN and, when $\varepsilon < \varepsilon_1$, model RY is formed in the CLSC. On this basis, because $\varepsilon_{sc2} > \varepsilon_1$, we know that the enterprises replace model RY with model C. Therefore, when the centralized decision-making method is introduced, enterprises only consider model C and model RN; when ε is larger than ε_{sc3}, enterprises choose model RN, and when the pollution level of waste product is relatively low, enterprises choose model C.

Further, because $\frac{\partial \varepsilon_{sc3}}{\partial \lambda} = -\frac{1}{2}\left(\frac{(1+2\lambda)(a-\beta c_m)^2}{8\beta m(1+\lambda)^2}\right)^{-\frac{1}{2}} \frac{\lambda(1+\lambda)(a-\beta c_m)^2 16\beta m}{\left(8\beta m(1+\lambda)^2\right)^2} < 0$, the increase in λ reduces the value of ε_{sc3}, which means a rise in the degree of retailer fairness concern is not conducive to forming an enterprise alliance.

(3)

$$SW^{N*} = SW^{RY*} = \frac{7(a-\beta c_m)^2}{32\beta} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{m}{4} - \frac{\varepsilon(a-\beta c_m)}{4};$$

$$SW^{RN*} - SW^{RY*} = \frac{\lambda\varepsilon(a-\beta c_m)}{4(1+\lambda)} - \frac{\left(7\lambda^2+6\lambda\right)(a-\beta c_m)^2}{32\beta(1+\lambda)^2},$$

when $\varepsilon > \varepsilon_{s1}$, $SW^{RN*} - SW^{RY*} > 0$, otherwise $SW^{RN*} - SW^{RY*} < 0$; $SW^{C*} - SW^{RY*} = \frac{5(a-\beta c_m)^2}{32\beta} - \frac{\varepsilon(a-\beta c_m)}{4}$, when $\varepsilon_{s2} > \varepsilon$, $SW^{C*} - SW^{RY*} > 0$, otherwise $SW^{C*} - SW^{RY*} < 0$; $SW^{C*} - SW^{RN*} = \frac{\left(5+12\lambda^2+16\lambda\right)(a-\beta c_m)^2}{32\beta(1+\lambda)^2} - \frac{(1+2\lambda)\varepsilon(a-c_m\beta)}{4(1+\lambda)}$, when $\varepsilon_{s3} > \varepsilon$, $SW^{C*} - SW^{RN*} > 0$, otherwise $SW^{C*} - SW^{RN*} < 0$.

From $\varepsilon_{s1} - \varepsilon_{s2} = \frac{(2\lambda+1)(a-\beta c_m)}{8\beta(1+\lambda)} > 0$, $\varepsilon_{s1} - \varepsilon_{s3} = \frac{\left(4\lambda+1+5\lambda^2+2\lambda^3\right)(a-\beta c_m)}{8\beta(1+\lambda)(1+3\lambda+2\lambda^2)} > 0$,

$\varepsilon_{s3} - \varepsilon_{s2} = \frac{\left(2\lambda^2+\lambda\right)(a-\beta c_m)}{8\beta(1+3\lambda+2\lambda^2)} > 0$, we know that $\varepsilon_{s1} > \varepsilon_{s3} > \varepsilon_{s2}$. This means that, when

$$\varepsilon < \varepsilon_{s2},\ SW^{C*} > SW^{RY*} = SW^{N*} > SW^{RN*};$$

when $\varepsilon_{s2} < \varepsilon < \varepsilon_{s3}$, $SW^{RY*} = SW^{N*} > SW^{C*} > SW^{RN*}$;

when $\varepsilon_{s3} < \varepsilon < \varepsilon_{s1}$, $SW^{RY*} = SW^{N*} > SW^{RN*} > SW^{C*}$;

when $\varepsilon > \varepsilon_{s1}$, $SW^{RN*} > SW^{RY*} = SW^{N*} > SW^{C*}$. □

Proof of Proposition 5: The retailer's utility under coordination is as follows:

$$\begin{array}{c} U_r^T = (1+\lambda)((a-\beta p)(p-w)+(b-p_c)(\theta+mp_c)-F) \\ -\lambda((a-\beta p)(w-c_m)+(\Delta-b+s)(\theta+mp_c)+F) \end{array} \tag{A15}$$

Through Equation (A15), the Hessian matrix of $U_r^T(p, p_c)$ is obtained:

$$H = \begin{bmatrix} \partial^2 U_r^T/\partial p^2 & \partial^2 U_r^T/\partial p \partial p_c \\ \partial^2 U_r^T/\partial p_c \partial p & \partial^2 U_r^T/\partial {p_c}^2 \end{bmatrix} = \begin{bmatrix} -2(1+\lambda)\beta & 0 \\ 0 & -2(1+\lambda)m \end{bmatrix}$$

Because $-2(1+\lambda)\beta < 0$ and $4(1+\lambda)^2\beta m > 0$, $U_r^T(p, p_c)$ is concave in p and p_c. By solving Equation (A15) with the condition that the first derivative is zero, we can derive the retailer's reaction as follows:

$$p^T = \frac{a}{2\beta} + \frac{(1+2\lambda)w}{2(1+\lambda)} - \frac{\lambda c_m}{2(1+\lambda)},\ p_c^T = \frac{(1+2\lambda)b}{2(1+\lambda)} - \frac{\theta}{2m} - \frac{\lambda\Delta}{2(1+\lambda)} - \frac{\lambda s}{2(1+\lambda)}$$

Then, letting $p^T = p^{C*}$, $p_c^T = p_c^{C*}$, and $s^T = s^{C*}$, we obtain the following:

$$w^T = c_m,\ b^T = \Delta + \varepsilon$$

Substituting s^{C*}, p^{C*}, p_c^{C*}, w^T, and b^T into Equations (6)–(8), the two enterprises' profits and the retailer's utility can be obtained:

$$\pi_r^T = \frac{(a-\beta c_m)^2}{4\beta} + \left(\frac{\theta}{m} + \Delta + \varepsilon\right)^2 \frac{m}{4} - F \tag{A16}$$

$$\pi_m^T = F \tag{A17}$$

$$U_r^T = \frac{(1+\lambda)(a-\beta c_m)^2}{4\beta} + \left(\frac{\theta}{m} + \Delta + \varepsilon\right)^2 \frac{(1+\lambda)m}{4} - (1+2\lambda)F \tag{A18}$$

□

Proof of Proposition 6: The coordination for model RY needs to meet the following:

$$\begin{cases} U_r^T \geq U_r^{RY} \\ \pi_r^T \geq \pi_r^{RY} \\ \pi_m^T \geq \pi_m^{RY} \\ 0 < \varepsilon < \varepsilon_1 \end{cases}$$

That is,

$$\begin{cases} \frac{(3+3\lambda)(a-\beta c_m)^2}{16\beta(1+2\lambda)} \geq F \\ \frac{(3+4\lambda)(a-\beta c_m)^2}{16\beta(1+2\lambda)} - \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{\lambda m}{(2+4\lambda)} \geq F \\ F \geq \frac{(1+\lambda)(a-\beta c_m)^2}{8\beta(1+2\lambda)} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{(1+\lambda)m}{(2+4\lambda)} \\ 0 \leq \varepsilon \leq \sqrt{\frac{\lambda(a-\beta c_m)^2}{8\beta m(1+\lambda)^2}} - \left(\frac{\theta}{m} + \Delta\right) \end{cases}$$

By simplifying, the coordination for model RY needs to meet the following:

$$\frac{(1+\lambda)(a-\beta c_m)^2}{8\beta(1+2\lambda)} + \left(\Delta + \frac{\theta}{m} + \varepsilon\right)^2 \frac{(1+\lambda)m}{2(1+2\lambda)} \leq F \leq \frac{(3+3\lambda)(a-\beta c_m)^2}{16\beta(1+2\lambda)}$$

The coordination for model RN needs to meet the following:

$$\begin{cases} U_r^T \geq U_r^{RN} \\ \pi_r^T \geq \pi_r^{RN} \\ \pi_m^T \geq \pi_m^{RN} \\ \varepsilon_1 < \varepsilon < \varepsilon_{sc3} \end{cases}$$

That is,

$$\begin{cases} \frac{\left(3+4\lambda^2+8\lambda\right)(a-\beta c_m)^2}{16\beta(1+\lambda)(1+2\lambda)} \geq F \\ \frac{\left(3+4\lambda^2+6\lambda\right)(a-\beta c_m)^2}{16\beta(1+\lambda)^2} - \frac{\lambda m}{2}\left(\frac{\theta}{m}+\Delta+\varepsilon\right)^2 \geq F \\ \frac{(a-\beta c_m)^2}{8\beta(1+\lambda)} + \left(\frac{\theta}{m}+\varepsilon+\Delta\right)^2 \frac{m(1+\lambda)}{2} \leq F \\ \sqrt{\frac{\lambda(a-\beta c_m)^2}{8\beta m(1+\lambda)^2}} - \left(\Delta+\frac{\theta}{m}\right) \leq \varepsilon \leq \sqrt{\frac{(1+2\lambda)(a-\beta c_m)^2}{8\beta m(1+\lambda)^2}} - \left(\Delta+\frac{\theta}{m}\right) \end{cases}$$

Same as above, we can obtain the condition of model RN's coordination as follows:

$$\frac{(a-\beta c_m)^2}{8\beta+8\beta\lambda} + \left(\frac{\theta}{m}+\varepsilon+\Delta\right)^2 \frac{m(1+\lambda)}{2} \leq F \leq \frac{\left(3+4\lambda^2+8\lambda\right)(a-\beta c_m)^2}{16\beta(1+\lambda)(1+2\lambda)}$$

□

Proof of Proposition 7:

(1)

$\frac{\partial F_{\min}^{RY}}{\partial \varepsilon} = \left(\varepsilon+\Delta+\frac{\theta}{m}\right)\frac{m(1+\lambda)}{1+2\lambda} > 0$, $\frac{\partial F_{\min}^{RN}}{\partial \varepsilon} = (1+\lambda)(m\varepsilon+\theta+m\Delta) > 0$;

$\frac{\partial F_{\min}^{RY}}{\partial \lambda} = -\frac{(a-\beta c_m)^2 8\beta}{(8\beta(1+2\lambda))^2} - \frac{2m\left(\Delta+\frac{\theta}{m}+\varepsilon\right)^2}{(2(1+2\lambda))^2} < 0$;

$\frac{\partial F_{\min}^{RN}}{\partial \lambda} = \left(\frac{\theta}{m}+\varepsilon+\Delta\right)^2 \frac{m}{2} - \frac{(a-\beta c_m)^2}{8\beta(1+\lambda)^2}$, when $\varepsilon > \sqrt{\frac{(a-\beta c_m)^2}{4m\beta(1+\lambda)^2}} - \left(\frac{\theta}{m}+\Delta\right)$, $\frac{\partial F_{\min}^{RN}}{\partial \lambda} > 0$,

otherwise $\frac{\partial F_{\min}^{RN}}{\partial \lambda} < 0$.

(2)

$$\frac{\partial F_{\max}^{RY}}{\partial \varepsilon} = 0,\ \frac{\partial F_{\max}^{RN}}{\partial \varepsilon} = 0,\ \frac{\partial F_{\max}^{RY}}{\partial \lambda} = -\frac{48\beta(a-\beta c_m)^2}{(16\beta(1+2\lambda))^2} < 0,$$

$$\frac{\partial F_{\max}^{RN}}{\partial \lambda} = \frac{-\left(1+4\lambda+4\lambda^2\right)}{\left(16\beta(1+3\lambda+2\lambda^2)\right)^2}(a-\beta c_m)^2 16\beta < 0.$$

□

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