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Pricing and Coordination of Green Closed-Loop Supply Chain With Fairness Concerns

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ABSTRACT Due to serious environmental pollution and waste of resources, the government advocates the development of a sustainable circular economy, and academia and manufacturing are gradually paying attention to the green closed-loop supply chain. In this paper, a green closed-loop supply chain consisting of a manufacturer and a retailer is considered. The manufacturer would cost a great deal to recycle waste products for remanufacturing while developing and producing green products, which may concern about the fairness of the profit distribution. Based on game theory, four different game scenarios are proposed, which are a centralized model and three decentralized models including manufacturer considering fairness neutrality, the retailer considering manufacturer's fairness concerns and the retailer ignoring manufacturer's fairness concerns. This paper compares and analyzes the optimal decision-making of the manufacturer and retailer in different scenarios, discusses the impact of manufacturer's fairness concerns on various decision variables, the profits of supply chain members and the overall profits, and then studies the effect of green efficiency on green closed-loop supply. The results show that this behavior would cause less damage to the green closed-loop supply chain and is more conducive to ensuring the environmental quality of green products, recycling and reuse of waste products and consumer rights when the retailer considers the manufacturer's fairness concerns behavior. By designing a revenue-sharing contract to coordinate the supply chain, it can effectively achieve the Pareto improvement of the green closed-loop supply chain with fairness concerns.

INDEX TERMS Fairness concerns, decision-making, green closed-loop supply chain, revenue-sharing contract.

I. INTRODUCTION

As technological progress and economic growth continue to promote the development of the supply chain, the problems of environmental pollution and resource shortage continue to worsen. In 2020, Chinese government proposed that manufacturers should actively design green product and strive to meet the requirements of green production in the revised ''Solid Waste Environmental Pollution Prevention and Control Law''. Through the joint efforts of various countries, many international companies have begun to adopt green closed-loop supply chain management [1], [2]. For example, Hewlett-Packard chooses environmentally friendly materials to manufacture products, and is committed to the recycling of waste products and the development of circular economy. Ford takes ''Better World'' as its corporate culture aiming to realize the sustainable development of the company, the environment and the community. Samsung usually conducts business with suppliers that qualify as green partners, and promises that ''protecting the earth is our first consideration''. Another factor that the leadership in the supply chain system would affect the distribution of channel profits. Most current researches regard manufacturers as the leader in the closed-loop supply chain. In the real business environment, as the market gradually centers on consumer demand and the retail industry is gaining momentum, some supply chain leaders have transformed from manufacturer to retailer, such as Suning, Amazon and Alibaba, etc. Also retailers usually show greater concern about fairness in reality, which the fairness concern behavior of enterprises has been regarded a major influence on the stability and efficiency of the supply chain. Therefore, this paper studies the pricing decision of green

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closed-loop supply chain under the retailer leader structure, and explores how to coordinate and realize the win-win of node enterprises with fairness concerns in the supply chain.

In the actual operation of the green closed-loop supply chain, the node companies of the supply chain concern about the fairness of the profit distribution. As early as 1979, a group of scientists proposed this view after extensive research: People often show great concern about fairness in reality, which is called fairness concerns [3]. In 2017, Thaler was awarded the Nobel Prize in Economics for his long-term contributions to the research directions of bounded rationality and social preferences, which is also enough to show the affirmation and attention to the topic of bounded rationality. With the continuous progress of scientific research and the continuous enrichment of research results, more and more scholars have begun to discuss the fairness concerns in the bounded rationality of closed-loop supply chain [4], [5]. Compared with most supply chain research models, those research considers fairness concern behavior goes beyond the assumption of ''rational man'' in traditional model, where decision-making participants may not make decisions based on their own profit maximization. This is also more realistic, people often not only pay attention to their own utility, but also pay attention to the utility of their stakeholders. For example, in the early days of Wal-Mart and Procter & Gamble, unfair distribution of benefits led to unhappiness and even conflict; the ''Price War'' continued to affect the relationship between GOME and GREE due to their inconsistent profits in future development goals. Therefore, the fairness concern behavior of enterprises plays a vital role in the cooperation, stability and efficiency of supply chain enterprise.

The green closed-loop supply chain develops from the perspectives of green supply chain and closed-loop supply chain. In the green supply chain, the green degree is used to assess the green products as a decision variable when manufacturer decides how the products are grown or made [6], [7]. In the closed-loop supply chain, the recycling channels of waste products are studied [8], [9]. At present, there are many studies on fairness concern behaviors, and most of them are based on the assumption that members of the traditional supply chain have fairness concern behaviors [10], [11]. With the deepening of research and the enrichment of practical background, scholars gradually introduce fairness concerns into the green supply chain and closed-loop supply chain [12], [13], but few studies introduced fairness concerns into green closed-loop supply chains. In order to research the problem more concisely and directly, a green closed-loop supply chain composed of a manufacturer and a retailer is constructed, where the manufacturer often invests in green R&D, production, recycling and remanufacturing, which is more likely to have fairness concerns. In the context of the above practice and academic research, it is necessary to consider the fairness concerns of members in the green closed-loop supply chain. Therefore, this paper would make the following contributions: (1) Discussing the impact of this behavior on the decision-making and profit distribution of members in the green closed-loop supply chain when the retailer considers or ignores the manufacturer's fairness concern behavior; (2) Analyzing the effect of green efficiency on the members of the green closed-loop supply chain in the pricing process; (3) Designing corresponding contracts to coordinate the green closed-loop supply chain under the influence of fairness concerns.

The structure of this paper is as follows: The section 2 is a literature review. Section 3 describes the problem and related symbolic assumptions. Decision models that considers fairness concerns behavior in a green closed-loop supply chain are constructed in section 4. Section 5 analyzes and compares the equilibrium results of each decision model. A revenue-sharing contract is designed to coordinate the green closed-loop supply chain in section 6. The section 7 verifies the previous conclusions by numerical simulation. The section 8 summarizes the full text.

II. LITERATURE REVIEW

The critical issue is decision-making game in supply chain, which has attracted considerable attention in academia and practice. Scholars have conducted research from multiple perspectives, such as strategic inventory [14], fresh-product supply chain [15]–[17], government subsidies [18], [19], recycling channel selection [8], [20], consumer preferences [21], etc. In response to the research questions in this paper, the decision-making and coordination of green closed-loop supply chain, and coordination of supply chain with fairness concern are reviewed.

A. DECISION-MAKING AND COORDINATION OF GREEN CLOSED-LOOP SUPPLY CHAIN

Some scholars have researched relevant pricing and coordination issues about green supply chain and closed-loop supply chain. For example, Xie [22] studied the impact of government subsidies on the green degree and price of environmentally friendly products under two different structures and used a revenue-sharing contract to improve the supply chain. Hafezalkotob and Zamani [23] studied the impact of government financial intervention and pricing in the green supply chains and used genetic algorithms to analyze the results. Dey and Saha [24], Dey *et al.* [25] discussed the optimal pricing and product green decision in the two-period green supply chain, and found that the retailer's purchasing decision is a key factor in the Manufacturer-Stackelberg vertical game. Yang *et al.* [26] studied the impact of manufacturer's green investment on product quality levels and the optimal pricing decisions of the manufacturer and retailer in the supply chain, and found that the manufacturer is more willing to invest green cost with lower green sensitivity. As the high price of green products is not conducive to demand, Yanju *et al.* [27] analyzed the impact of wholesale price contracts, cost-sharing contracts, and two-part contracts on green product demand, supply chain member profits, and channel profits in a retailer-led bilateral monopoly green supply chain.

Most papers use product green degree to represent typical characteristics of the green supply chain. Some scholars have also researched pricing and coordination of closed-loop supply chain. Savaskan *et al.* [28] established decentralized decision models and proved that closed-loop supply chain systems could be improved without requiring complicated coordination mechanisms. Afterwards, Savaskan and Van Wassenhove [29] further researched and analyzed the pricing decisions under retailer recycling and manufacturers' direct recycling. Giovanni [30] researched two incentive game models through revenue sharing contracts in the manufacturer-led closed-loop supply chain and found that endogenous incentives in the supply chain would not be more favorable than non-incentive situations, on the contrary, exogenous incentives could bring additional benefits to the supply chain within a specific range. Zou and Liu [31] studied supply chain decision-making under different post-purchase guarantee models, and proposed a revenue-sharing contract to coordinate supply chain performance. Giri *et al.* [32] studied the closed-loop supply chain consisting of a manufacturer and a retailer, and compared the impact of factors such as sales price, product warranty period and product green degree on product market demand. Saha *et al.* [33] investigated the influence of government incentives on a closed-loop supply chain which considering greening level of the product, and found that the greening level and used product return rate in closed-loop supply chain would always higher under Retailer-Stackelberg game. Zhang *et al.* [34] introduced the defective item return and waste product return in the dual-channel closed-loop supply chain, and designed a revenue-sharing contract to motivate retailer's efforts in recycling waste products. Ranjbar *et al.* [35] evaluated optimal pricing and collection decisions under different power structures with two competitive recycling channels including retailer collecting and third-party collector collecting, and found that the retailer leadership model would be the best. Zerang *et al.* [36] analyzed and compared the two-part tariff, cost sharing and revenue cost-sharing contracts under asymmetric and symmetric information.

B. SUPPLY CHAIN PRICING AND COORDINATION CONSIDERING FAIRNESS CONCERNS

Many literatures on the decision-making and coordination of the green closed-loop supply chain was researched under the premise that all decision-makers are "rational people". Through the proof of theory and practice, decision-makers in reality often have irrational psychological tendencies. Haitao Cui *et al.* [37] discussed the impact of fairness concerns on retailer-led supply chain, and found that manufacturer only needed to give a constant wholesale price higher than the manufacturing cost to improve supply-chain efficiency. Zheng *et al.* [38] assumed that the retailer had fairness concern behavior, and a cooperative game mechanism was designed to coordinate the profit distribution among members of a third-echelon closed-loop supply chain consisting of a manufacturer, a distributor and a retailer. Cao *et al.* [13] analyzed the influence of fairness concern behaviors on closed-loop supply chain, and adopted revenue sharing contract to achieve obviously Pareto improvement. Qin *et al.* [39] explored the impact of the retailer's fairness concerns on wholesale price, orders and profit, and proposed some suggestions on optimizing the supply chain. Adopting the game-theory analysis framework, Li *et al.* [40] explored the optimal decisions of transfer price and collection effort in the fair RSC model and discussed the impacts of fairness concern when they studied distributional fairness and peer-induced fairness in a reverse supply chain. Yan *et al.* [41] discussed the impact of the fairness concerns on the pricing and freshness preservation efforts and used a revenue sharing contract to achieve the Pareto improvement under the traditional framework and the Nash bargaining framework in the manufacturer-led fresh agricultural products supply chain. Li *et al.* [42] investigated the impact of the retailer's fairness concern by comparing the optimal solutions and supply chain performance and found that retailer's fairness concern would always harm the manufacturer. Qian *et al.* [43] focused on a channel coordination problem in a two-echelon sustainable supply chain involving socially responsible manufacturer. Considering the level of suppliers' effort performance and behavior of fairness concern, Liu *et al.* [44] analyzed and compared the supply chain decisions under different scenarios, and designed a cost sharing contract to coordinate the supply chain.

The above reviews the literature related to this study about green supply chain and closed-loop supply chain. There are relatively few literatures with green closed-loop supply chains as the research background. In addition, research on supply chain rarely discussed the fairness concerns of member under different leadership. This paper pays attention to the retailer-led green closed-loop supply chain and considers the fairness concerns of the manufacturer. Through model construction and result analysis, the pricing decisions of supply chain in different situations are discussed. Finally, the appropriate contract is designed to coordinate the green closed-loop supply chain.

III. PROBLEM DESCRIPTION AND ASSUMPTIONS

A two-echelon green closed-loop supply consisting of a retailer (R) and a manufacturer (M) are considered. According to practical case, M is responsible for R&D and production of green products, who pays the cost too. In addition, many manufacturers take the initiative to assume environmental protection and social responsibilities, and actively establish recycling systems to recycle waste products, such as Tesla, Apple, HUAWEI, etc. R is the leader in the green closed-loop supply chain and is responsible for selling green products. This paper establishes a pricing decision model based on the Stackelberg game. The game sequence between R and M is as follows: 1) As a leader, R first determines the unit profit obtained by selling green products. Then M determines the unit wholesale price, and the unit retail price of the product can be obtained; 2) As a follower,

TABLE 1. Definition of symbols.

Symbols	Definition	Symbols	Definition
c_m	Production cost of new products, $c_m > 0$;	c_r	Production cost of remanufactured products, $c_r > 0$;
w	Unit wholesale price of products, $w > 0$;	g	Product green degree, $g > 0$;
τ	Recycling rate of waste product, $0 \le \tau < 1$;	h	R's unit profit, $h > 0$;
p	Unit retail price of products, $p = w + h$;	$c_{(\tau)}$	M's recycling effort cost, $c_{(\tau)} = k\tau^2$, k represents the difficulty of recycling waste products, $k > 0$;
D	Market demand, $D = a - p + \alpha g$, $a > 0$, $\alpha > 0$, a is the potential market demand, α is the consumer's green preference coefficient;	I	M's green investment cost, $I = \beta g^2$, $\beta > 0$, representing the manufacturer's green product R&D coefficient;
π_r	R's profit;	π_m	M's profit;
π_s	Profit of the green closed-loop supply chain system, $\pi_s = \pi_r + \pi_m$;	λ_m	M's fairness concerns coefficient, $\lambda_m > 0$;
u_m	M's fairness concerns utility;		

M would determine the wholesale price of green product, the product green degree and the recycling rate of waste products, so as to the profit of M, R and green closed-loop supply chain can be obtained. The definition of related symbols in this article are showed in Table 1.

In reality, many companies choose the Target-Return Pricing, such as mobile phone retailers and home appliance retailers. Many scholars regard the unit profit of the product as a decision variable in the research process [9], [45], [46]. Therefore, the decision variables in this paper are the wholesale price w, the product green degree g, the recycling rate of waste product τ, R's unit profit h, and the unit retail price$p$. For readability, in this paper, (1) "C" is used to represent the centralized decision-making model; (2) "D1" is used to represent the decentralized decision-making model of M's fairness neutrality; (3) "D2" represents the decentralized decision-making model that R considers M's fairness concerns; (4) "D3" represents the decentralized decision-making model that R ignores M's fairness concerns. To analyze the model, the following assumptions are listed:

1) To generate economic benefits for the recycling and remanufacturing of waste products, let $c_m - c_r > 0$; In the actual green closed-loop supply chain, most companies prefer environmentally friendly materials in the product design and production stage, which are easy to disassemble and reuse after recycling, such as the recycling, dismantling and utilization of raw materials for Tesla car battery, and the selection and recycling of environmentally friendly materials for Huawei electronic products. Most of remanufacturing process indicates that new products are produced by recycled materials. To distinguish it from new product, it is called remanufactured product. In fact, remanufactured products are the same as new product. Therefore, the unit wholesale price and unit retail price of the remanufactured product and the new product are the same.

2) Consumers usually pay more attention to the price of green products and the degree of environmental protection of the product, so the market demand for green products is affected by the retail price and the product green degree. The method of Liu *et al.* [47] and Swami and Shah [48] is referred to set the market demand to $D = a - p + \alpha g$, $a - p > 0$.

3) Refer to the method [12], the product green efficiency coefficient is defined as $\frac{\alpha^2}{\beta}$, where α is the consumer green preference coefficient and β is the R&D cost coefficient of M's green product. The product green efficiency coefficient satisfies $0 < \frac{\alpha^2}{\beta} < 4$. When $0 < \frac{\alpha^2}{\beta} < 2$, it means low greening efficiency; when $2 < \frac{\alpha^2}{\beta} < 4$, it means high greening efficiency.

IV. DECISION-MAKING MODEL

In this section, the equilibrium results of the centralized and decentralized decision-making model are solved, where the M's fairness neutrality and fairness concerns are considered.

A. CENTRALIZED DECISION-MAKING MODEL(C)

In the C model, both parties work together to achieve the best system profit of supply chain. Firstly, the overall profit of the green closed-loop supply chain is determined. Secondly, according to the theory of Hessian matrix, the optimal equilibrium result of each decision variable can be solved.

Therefore, the system profit function of C model is as follows:

$$\pi^{C}_{s(p,\tau,g)} = (p - (1-\tau)\, c_m - c_r\tau)\,(a - p + \alpha g) - k\tau^2 - \beta g^2 \tag{1}$$

The Hessian matrix of equation (1) with respect p, τ, and g is listed as follows:

$$H^C = \begin{pmatrix} -2 & c_r - c_m & \alpha \\ c_r - c_m & -2k & \alpha(c_m - c_r) \\ \alpha & \alpha(c_m - c_r) & -2\beta \end{pmatrix}$$

The value of the Hessian matrix is: $2k\left(\alpha^2 - 4\beta\right) + 2\beta\,(c_m - c_r)^2$. Only when k is large enough and the condition $k > \frac{(c_m-c_r)^2}{4-\alpha^2/\beta}$ is satisfied, H^C is negative definite and the model can be established. Therefore, $\pi^{C}_{s(p,\tau,g)}$ is a strictly concave function about p, τ, and g, and there is a unique optimal solution for the system profit function.

Solving partial derivatives of equation (1) with respect to p, τ, and g, the optimal values of recycling rate, product green degree, retail price, and product demand can be obtained as follows:$\tau^{C*} = \frac{(a-c_m)(c_m-c_r)}{A}$, $g^{C*} = \frac{k\alpha(a-c_m)}{\beta A}$, $p^{C*} = a - \frac{B}{A}$, $D^{C*} = \frac{2k(a-c_m)}{A}$. Substituting the above optimal decision value into equation (1), the optimal system profit is obtained: $\pi_s^{C*} = \frac{k(a-c_m)^2}{A}$. In the above equilibrium results, $A = k\left(4 - \alpha^2/\beta\right) - (c_m - c_r)^2$, $B = k\left(2 - \alpha^2/\beta\right)(a - c_m)$.

B. DECENTRALIZED DECISION-MAKING MODEL

1) DECISION-MAKING MODEL OF M's FAIRNESS NEUTRALITY(D1)

In the model of M's fairness neutrality, R and M are still viewed from the perspective of the traditional rational "economist", so R and M do not reach the common goal of achieving the best overall benefit of the supply chain and their own optimal benefits. Firstly, R decides the unit sale profit of green products. Secondly, M determines the wholesale price, the product green degree and the recycling rate of waste products. Finally, the retail price, the profits of M, R and the whole green closed-loop supply chain are obtained. Therefore, the profit functions of R, M and supply chain system are as follows:

$$\pi_{r(p)} = (p - w)\,(a - p + \alpha g) \tag{2}$$

$$\pi_{m(w,\tau,g)} = (w - (1-\tau)\, c_m - c_r\tau)\,(a - p + \alpha g) - k\tau^2 - \beta g^2 \tag{3}$$

$$\pi_s = \pi_r + \pi_m \tag{4}$$

The model was solved by using the reverse induction method in D1 model. Substituting $p = w + h$ into M's profit function and solving the second derivative of M' profit function with respect to w, τ, and g, then $\frac{\partial^2\pi_m}{\partial w^2} = -2 < 0$, $\frac{\partial^2\pi_m}{\partial \tau^2} = -2k < 0$, $\frac{\partial^2\pi_m}{\partial g^2} = -2\beta < 0$ can be obtained. Therefore, M's profit is a strictly concave function of w, τ, and g. From the first-order condition the following can be obtained:

$$w = a - h - \frac{k\left(2 - \alpha^2/\beta\right)(a - h - c_m)}{k\left(4 - \alpha^2/\beta\right) - (c_m - c_r)^2} \tag{5}$$

$$\tau = \frac{(a - h - c_m)\,(c_m - c_r)}{k\left(4 - \alpha^2/\beta\right) - (c_m - c_r)^2} \tag{6}$$

$$g = \frac{k\alpha\,(a - h - c_m)}{\beta\left(k\left(4 - \alpha^2/\beta\right) - (c_m - c_r)^2\right)} \tag{7}$$

Substituting equations (5), (6), (7) and $p = w + h$ into R's profit function, and taking the second derivative of R's profit with respect to h.

From the first-order condition, the optimal unit profit $h^{D1*} = \frac{1}{2}(a - c_m)$ can be derived; Substituting it into equations (5), (6), (7), the optimal decisions of M can be obtained as follows: $w^{D1*} = \frac{1}{2}\left(a + c_m - \frac{B}{A}\right)$, $\tau^{D1*} = \frac{(a-c_m)(c_m-c_r)}{2A}$, $g^{D1*} = \frac{k\alpha(a-c_m)}{2\beta A}$. The optimal retail price is: $p^{D1*} = a - \frac{B}{2A}$. Substituting p^{D1*} and g^{D1*}into the market demand function, $D^{D1*} = \frac{k(a-c_m)}{A}$ can be got. Finally, the maximum profits of R, M, and the entire supply chain are: $\pi_r^{D1*} = \frac{k(a-c_m)^2}{2A}$, $\pi_m^{D1*} = \frac{k(a-c_m)^2}{4A}$, $\pi_s^{D1*} = \frac{3k(a-c_m)^2}{4A}$.

2) DECENTRALIZED DECISION-MAKING MODEL CONSIDERING M's FAIRNESS CONCERNS (D2)

In the green closed-loop supply chain, M needs to afford huge R&D costs of green products and the recycling effort costs of waste product, so M would be more concerned about whether the benefits M obtains are worth investing a lot of costs in product manufacturing and recycling. In addition, under the dominant model of R, M who is already in a weak position is very susceptible to doubt about the fairness of channel profit distribution. Therefore, it is necessary to consider the fairness concerns of M in green closed-loop supply chain.

When R considers M's fairness concerns, M's goal is to maximize own utility and R's goal is to maximize own profit. Similarly, R would first determine the unit profit. Secondly, after obtaining the unit profit, M determines the wholesale price, product green degree and recycling rate of waste product. Finally, the retail price, the profits of M, R and the whole green closed-loop supply chain can be obtained. The method of Du *et al.* [49] and Zhang *et al.* [50] can be used to build the utility function with M's fairness concerns as follows:

$$\mathrm{u}_m = \pi_m - \lambda_m\,(\pi_r - \pi_m) \tag{8}$$

In D2 model, the solution process is similar to Section 4.2.1 by reverse induction method, and the optimal decision variables of M are as follows: $w^{D2*} = \frac{1}{2}\left(\frac{a(1+3\lambda_m)+(1+\lambda_m)c_m}{1+2\lambda_m} - \frac{B}{A}\right)$, $\tau^{D2*} = \frac{(a-c_m)(c_m-c_r)}{2A}$, $g^{D2*} = \frac{k\alpha(a-c_m)}{2\beta A}$. The optimal decision variables of R are: $h^{D2*} = \frac{(1+\lambda_m)(a-c_m)}{2+4\lambda_m}$, $p^{D2*} = a - \frac{B}{2A}$. The optimal market demand is: $D^{D2*} = \frac{k(a-c_m)}{A}$. Therefore, the optimal profits of both parties and the supply chain, and the maximum utility of M are respectively: $\pi_r^{D2*} = \frac{k(1+\lambda_m)(a-c_m)^2}{2(1+2\lambda_m)A}$, $\pi_m^{D2*} = \frac{k(1+4\lambda_m)(a-c_m)^2}{4(1+2\lambda_m)A}$, $\pi_s^{D2*} = \frac{3k(a-c_m)^2}{4A}$, $u_m^{D2*} = \frac{k(1+\lambda_m)(a-c_m)^2}{4A}$.

3) DECENTRALIZED DECISION-MAKING MODEL IGNORING M's FAIRNESS CONCERNS (D3)

In the previous section, the situation where R pays attention to M's fairness concerns is considered, but in fact R may ignore the M's fairness concerns, whether the situation would affect pricing is also worth investigating. In D3 model, R aims at own maximum profit, and believes that M also aims at own maximum profit. In fact, M aims at own maximum utility. R firstly determines the unit sale profit according to maximize R's profit. Secondly, M determines the wholesale price, product green degree and recycling rate of waste product according to the optimal unit profit. And finally the retail price, the profits of M, R and the whole green closed-loop supply chain are obtained by the reverse induction method. The profit functions of the supply chain and the both parties and M's utility function are the same as D2 model. In D3 model, the R's optimal unit profit is $h^{D3*} = \frac{1}{2}(a - c_m)$.

After M obtains R's pricing information, optimal decisions variables can be determined: $w^{D3*} = \frac{1}{2}\left(a + c_m - \frac{B}{(1+\lambda_m)A}\right)$, $\tau^{D3*} = \frac{(a-c_m)(c_m-c_r)}{2(1+\lambda_m)A}$, $g^{D3*} = \frac{k\alpha(a-c_m)}{2\beta(1+\lambda_m)A}$. The optimal retail price is: $p^{D3*} = a - \frac{B}{2(1+\lambda_m)A}$. The optimal market demand of green product is: $D^{D3*} = \frac{k(a-c_m)}{(1+\lambda_m)A}$; Finally, the optimal profits of M, R and the supply chain and the optimal utility of M are as follows: $\pi_r^{D3*} = \frac{k(a-c_m)^2}{2(1+\lambda_m)A}$, $\pi_m^{D3*} = \frac{k(1+2\lambda_m)(a-c_m)^2}{4(1+\lambda_m)^2A}$, $\pi_s^{D3*} = \frac{k(3+4\lambda_m)(a-c_m)^2}{4(1+\lambda_m)^2A}$, $u_m^{D3*} = \frac{k(a-c_m)^2}{4(1+\lambda_m)A}$.

V. RESULT ANALYSIS

This section would analyze the equilibrium results of centralized and decentralized decision-making model.

Property 1: $\frac{\partial w^{D2*}}{\partial \lambda_m} > 0$, $\frac{\partial \tau^{D2*}}{\partial \lambda_m} = 0$, $\frac{\partial g^{D2*}}{\partial \lambda_m} = 0$, $\frac{\partial p^{D2*}}{\partial \lambda_m} = 0$, $\frac{\partial D^{D2*}}{\partial \lambda_m} = 0$.

Property 1 shows that the wholesale price increases with the increase of M's fairness concerns, while the remaining decision variables and market demand are not affected by M's fairness concerns behavior. This indicates that M chooses to increase profit by increasing the wholesale price in model D2. However, M still keeps the green input costs unchanged, and has not resorted to reducing green R&D costs to protest the fairness of channel profit distribution. This displays that, when R considers M's fairness concerns, M would adhere to the principle of protecting the environment and develop and produce high-quality green products. As R takes into account M's fairness concerns, it decides to increase the wholesale price in face of M's decision, but does not increase the retail price. This shows that R would also contribute to support M to develop and produce green products and can satisfy the fairness psychology of M by reducing own profit.

Property 2: $\frac{\partial \pi_m^{D2*}}{\partial \lambda_m} > 0$, $\frac{\partial \pi_r^{D2*}}{\partial \lambda_m} < 0$, $\frac{\partial \pi_s^{D2*}}{\partial \lambda_m} = 0$, $\frac{\partial u_m^{D2*}}{\partial \lambda_m} > 0$.

Property 2 shows that when R considers M's fairness concerns, R's profit would decrease with the increase of fairness concerns. On the contrary, M's profit and utility would increase with the increase of fairness concerns. Because M pays more attention to the fairness of channel profit distribution, the wholesale price increases. But the product green degree and retail price have not changed, the market demand of green products would not be affected, which leads to the decline of R's profit. Although the profits of both parties are affected by M's fairness concerns behavior, the system profit remains unchanged. The reason behind this is that changes in wholesale prices would only affect the profit distribution of M and R within the green closed-loop supply chain, and the decreased profit of R and the increased profit of M are equal in amount.

Property 3: $\frac{\partial \tau^{D3*}}{\partial \lambda_m} < 0$, $\frac{\partial g^{D3*}}{\partial \lambda_m} < 0$, $\frac{\partial D^{D3*}}{\partial \lambda_m} < 0$.

Property 3 shows that when R ignores M's fairness concerns behavior, the product green degree, recycling rate of waste product and market demand decrease with the increase of M's fairness concerns coefficient. Therefore, when M has fairness concerns, if R does not consider the psychological change of M, then M would feel even more disappointed and choose to reduce the investment of green costs to protect own interests from being harmed, which would result in a reduction in the product greenness. On the one hand, with the increasing awareness of consumers' environmental protection, the market demand decreases with the increase of fairness concerns. On the other hand, the recycling rate of waste products would also decrease, which increases the possibility of waste products polluting the environment. In short, the decisions made by M are to safeguard own interests and protest the fairness of channel profit distribution.

*Property 4:*When $0 < \frac{\alpha^2}{\beta} < 2$, there is $\frac{\partial w^{D3*}}{\partial \lambda_m} = \frac{\partial p^{D3*}}{\partial \lambda_m} > 0$; when $2 < \frac{\alpha^2}{\beta} < 4$, there is $\frac{\partial w^{D3*}}{\partial \lambda_m} = \frac{\partial p^{D3*}}{\partial \lambda_m} < 0$; when $\frac{\alpha^2}{\beta} = 2$, there is $\frac{\partial w^{D3*}}{\partial \lambda_m} = \frac{\partial p^{D3*}}{\partial \lambda_m} = 0$.

Property 4 shows that in the D3 model, when greening efficiency is low, the wholesale price and retail price are positively correlated with M's fairness concerns; when the greening efficiency of the supply chain is high, the wholesale price and retail price are inversely related to the M's fairness concerns. When the greening efficiency of the supply chain is at the middle critical value of 2, neither the wholesale price nor the retail price would be affected by the M's fairness concerns. The phenomenon presented in property 4 has the following reasons: 1) In the case of low greening efficiency of products, the stronger the M's fairness concerns is, the more M would increase the unit profit of products and reduce the green cost investment in order to strive for more interests. In the face of the conservative decision making made by M, R would continue to increase the retail price of products by the same extent to alleviate the damage to M own interests; 2) When the greening efficiency of products is high, M chooses to reduce the wholesale price while reducing the cost of green input and maintaining M own interests. When R knows that M reduced wholesale price, R choses to reduce marginal revenue by the same amount in order to achieve small profits and fast turnover; 3) When the greening efficiency of the product is just a critical value of 2, the impact of the increased marginal benefits of M and R would cancel each other out, so both parties keep the previous decision unchanged.

Property 5: $\frac{\partial \pi_m^{D3*}}{\partial \lambda_m} < 0$, $\frac{\partial \pi_r^{D3*}}{\partial \lambda_m} < 0$, $\frac{\partial \pi_s^{D3*}}{\partial \lambda_m} < 0$, $\frac{\partial u_m^{D3*}}{\partial \lambda_m} < 0$.

Property 5 shows that when R ignores M's fairness concerns, the profits of both parties and the M's utility are inversely related to the fairness concerns coefficient. This indicates that M would rather give up some of own interests to maintain the fairness of channel profit distribution. Combining with Property 3, it can be seen that when R ignores M's fairness concerns, M decides to reduce product green degree and the recycling rate of waste product. Although this decision reduces the cost of green product development and production invested by M, it greatly reduces the demand of the product. Therefore, the profits of R and M would suffer losses due to M's fairness concerns, and the overall profits of the supply chain would also decrease. Therefore, in the real business environment, the leader of the supply chain channel should pay attention to the psychological changes to the partners, give appropriate comfort or encouragement, and lead the supply chain to develop in a healthy and sustainable direction.

*Corollary 1:*When R does not care about M's psychological changes, M's fairness concerns behavior is the biggest damage to the economic and environmental benefits of the entire supply chain. Therefore, as the leader of supply chain, R should always pay attention to the behavior preferences of other member companies and take active measures to guide the supply chain to reach a new balance.

Conclusion 1: When R and M are fairness neutrality, $\pi_r^{D1*} = 2\pi_m^{D1*}$.

It can be found that under decentralized decision-making model of M's fairness neutrality, R's profit is twice that of the M's profit. This is because R is in a dominant position with stronger bargaining power and more opportunities to lead the supply chain in a direction, which is beneficial to R. Therefore, R usually gains more profit than M. This conclusion is consistent with some of the findings by Yanju *et al.* [27].

Conclusion 2: When $0 < \frac{\alpha^2}{\beta} < 2$, there is $p^{D3*} > p^{D2*} = p^{D1*} > p^{C*}$; when $2 < \frac{\alpha^2}{\beta} < 4$, there is $p^{C*} > p^{D2*} = p^{D1*} > p^{D3*}$; when $\frac{\alpha^2}{\beta} = 2$, there is $p^{D3*} = p^{D2*} = p^{D1*} = p^{C*}$.

Conclusion 2 shows that the ratio of the retail price under centralized decision-making and decentralized decision-making is related to the products' greening efficiency, but the retail price in D2 model is always the same as that when M is fairness neutrality. The reasons are listed as follows:

1) When the greening efficiency is low, the retail price when R ignores M's fairness concerns is the largest. Because the market expansion effect is small, R chooses to increase retail price and marginal income in the "double marginal" effect. When R ignores M's fairness concerns, retail prices are greater than other three decision-making models.

2) When the greening efficiency is high, the retail price under centralized decision-making is higher than that under other three decentralized decision-making models. Because the market expansion effect is greater and consumers are more sensitive to green products, the market demand under centralized decision-making increases, which can appropriately alleviate the adverse effects of rising retail prices.

3) When the product greening efficiency is just the critical value of 2, the retail price in centralized decision-making and decentralized decision-making is equal, which is related to the product market capacity and not to consumers' green preferences.

Conclusion 3: When $\frac{(c_m-c_r)(a-c_r)}{4-\alpha^2/\beta} < k < \frac{\beta(c_m-c_r)^2(1+\lambda_m)}{2\beta+\alpha^2\lambda_m}$ and $0 < \frac{\alpha^2}{\beta} < 2$, there is $w^{D3*} > w^{D2*} > w^{D1*}$; when $k > \frac{\beta(c_m-c_r)^2(1+\lambda_m)}{2\beta+\alpha^2\lambda_m}$ and $0 < \frac{\alpha^2}{\beta} < 2$, there is $w^{D2*} > w^{D3*} > w^{D1*}$; when $k > \frac{(c_m-c_r)(a-c_r)}{4-\alpha^2/\beta}$ and $2 < \frac{\alpha^2}{\beta} < 4$, there is $w^{D2*} > w^{D1*} > w^{D3*}$.

Conclusion 3 shows that under the three decentralized decision-making models, the level of the optimal wholesale price is not only related to the difficulty of recycling waste products, but also related to the greening efficiency. When the greening efficiency is low, regardless of the difficulty of recycling waste products, the wholesale price under M's fairness neutrality is less than that under the decentralized decision of M's fairness concerns. This is because the market expansion is not obvious when the greening efficiency is low so that M with fairness concerns uses higher wholesale price as a means to increase M own returns. At the same time, the "double marginal" effect is exacerbated. When the greening efficiency is high, the comparison of the wholesale price under the three decentralized decision-making models was not affected by the difficulty of recycling waste products. The improvement of greening efficiency brings about the expansion of market. When M has fairness concerns and R realizes M's characteristics, M would continue to increase wholesale price to obtain a fair distribution of own profits.

Conclusion 4:$\tau^{C*} > \tau^{D1*} = \tau^{D2*} > \tau^{D3*}$, $g^{C*} > g^{D1*} = g^{D2*} > g^{D3*}$, $D^{C*} > D^{D1*} = D^{D2*} > D^{D3*}$.

Conclusion 4 shows that the recycling rate of waste product, product green degree, product demand and the overall profit of the supply chain under centralized decision-making model are all greater than those under decentralized decision-making model. When R ignores M's fairness concerns, the recycling rate of waste product, product green degree, market demand, and the profits of both parties and the supply chain system are at the lowest value. When R considers M's fairness concerns, the product green degree, recycling rate of waste product, market demand, and retail price do not change. In the case of centralized decision-making model, the system profit is the largest, which is consistent with the related research in the field of supply chain. Because incentive conflict and double marginal effect still exist in the supply chain system under decentralized decision-making model, while both parties make decision on the premise of prioritizing the system profit under centralized decision-making model. This also shows that if both parties in the supply chain all achieve the goal of the best overall performance of the supply chain and form a solid "super organization" [12], the overall profit of green closed-loop supply is greatly improved. Therefore, this paper designs contract to coordinate the supply chain relation between M and R.

VI. COORDINATION CONTRACT WITH FAIRNESS CONCERNS

The revenue sharing contract is that manufacturer proposes a wholesale price lower than the manufacturing cost to the retailer, and retailer shares part of the revenue to the manufacturer at the end of the sale, which makes the system profit the same as the profit under the centralized decision-making.

A. COORDINATION OF DECENTRALIZED DECISION-MAKING CONSIDERING M's FAIRNESS CONCERNS

Using the contract coordination to redistribute the system profit under centralized decision-making [51], the profit functions under the revenue-sharing contract between R and M can be obtained (Using θ to represent the coordination parameters of the revenue-sharing contract):

$$\pi_{rSC}^{C*} = \theta \pi_s^{C*} \tag{9}$$

$$\pi_{mSC}^{C*} = (1-\theta)\pi_s^{C*} \tag{10}$$

Under decentralized decision-making model, both R and M take their own profit maximization as decision-making goal. Therefore, if both R and M can accept and execute the revenue-sharing contract, it is necessary to determine that the revenue of both parties achieves Pareto improvement when the revenue sharing contract is executed. In other words, for both parties, the profits under the contract is more than that before the execution of the contract, and the mathematical expressions is listed as following:

$$\pi_{rSC}^{C*} > \pi_r^{D2*}, \pi_{mSC}^{C*} > \pi_m^{D2*} \tag{11}$$

Then it is simplified to:

$$\frac{\pi_m^{D2*}}{\pi_s^{C*}} < \theta < 1 - \frac{\pi_r^{D2*}}{\pi_s^{C*}} \tag{12}$$

When the contract parameter θ satisfies formula (12), the revenue-sharing contract is effective way to coordinate the supply chain, and the specific scope of the contract parameter θ is related to M's fairness concerns coefficient, and also related to the bargaining power of the channel members.

B. COORDINATION OF DECENTRALIZED DECISION-MAKING IGNORING M's FAIRNESS CONCERNS

The contract coordination in this model is the same as the coordination in the previous section. For both parties, the profits under the contract is better than that in model D3, the mathematical expressions is described as following (Using γ to represents the contract parameter):

$$\pi_{rSC}^{C*} > \pi_r^{D3*}, \pi_{mSC}^{C*} > \pi_m^{D3*} \tag{13}$$

Simplified to:

$$\frac{\pi_m^{D3*}}{\pi_s^{C*}} < \gamma < 1 - \frac{\pi_r^{D3*}}{\pi_s^{C*}} \tag{14}$$

When the contract parameters γ satisfies formula (14), the revenue-sharing contract can effectively coordinate the supply chain, and the specific scope of the contract parameters γ is also related to M's fairness concerns coefficient and the bargaining power of the channel members.

VII. NUMERICAL SIMULATION

To intuitively exhibit the impact of M's fairness concerns on member companies' pricing decision, numerical simulation is used to verify the conclusions obtained above. Drawing on the results [52]–[54], this paper would adopt multiple sets of values for simulation. In the above analysis, there are classifications of the difficulty of recycling waste products k and the greening efficiency $\frac{\alpha^2}{\beta}$. Therefore, some values in the following numerical analysis graphs need to be distinguished. The specific numerical values of each graph are listed in Table 2.

TABLE 2. Initial values.

Figure	Parameter					
	a	k	c_m	c_r	α	β
1, 2, 3(b), 4(a), 5, 6, 7	200	500	20	16	4	10
3(c), 4(b)					5	
3(a)	50	180	40	20	1	3

(1) The impact of fairness concerns on product green degree and recycling rate

When M has fairness concerns behavior, the impact of the behavior on the product green degree and the recycling rate of waste product is showed in Figure 1 and Figure 2. The figures clearly show that: if R considers M's fairness concerns, the recycling rate of waste product and product green degree are not affected by fairness concerns, which are the same as the values under the decentralized decision-making model of M's fairness neutrality. On the contrary, if R ignores M's fairness concerns, M would continue to reduce product green degree and recycling rate of waste product as the fairness concerns increases. The decisions would increasingly deviate from the levels under decentralized decision-making model of M's fairness neutrality.

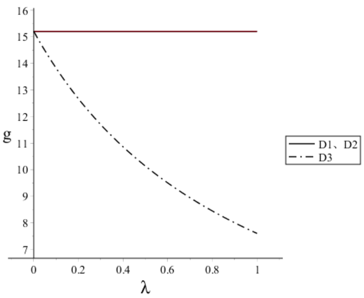


FIGURE 1. The impact of fairness concerns on product green degree.

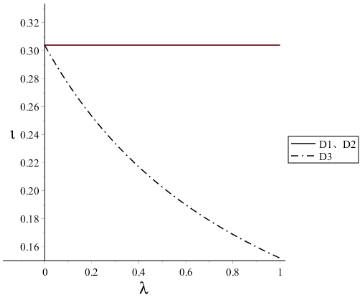


FIGURE 2. The impact of fairness concerns on the recycling rate of waste product.

(2) The impact of fairness concerns on wholesale price

When M has fairness concerns behavior, the impact of the behavior on the wholesale price of the product is showed in Figure 3. Figure indicates that: 1) When the greening efficiency of the supply chain is low, regardless of whether R is aware of M's fairness concerns, the wholesale price is positively related to M's fairness concerns, and it is always greater than the situation when M is fairness neutrality. This also shows that when the greening efficiency is low, M's fairness concerns helps to improve the bargaining power, so that M can continuously increase the wholesale price to obtain benefits. 2) When the greening efficiency of the supply chain is high, if R considers M's tendency of fairness concerns, then M would continue to increase the wholesale price. On the contrary, if R does not consider M's fairness concerns, then the wholesale price would continue to decrease as the level of fairness concerns increases.

(3) The impact of fairness concerns on retail price

When M has fairness concerns behavior, the impact of the behavior on the retail price of the product is showed in Figure 4. Figure displays that changes in retail price are not only related to M's fairness concerns, but also to R's attitudes toward M's fairness concerns and the greening efficiency of the supply chain. Therefore, in supply chain management, retailers as leaders should not only pay attention to manufacturers' behavior preferences, but also participate in the work of improving the greening efficiency of supply chain.

(4) The impact of fairness concerns on profits

When M has fairness concerns behavior, the impact of the behavior on the profits of M, R and the supply chain system is showed in Figures 5, 6, and 7. The figures demonstrate that the impact of M's fairness concerns on profits: 1) Only when R considers M's fairness concerns, the manufacturer would get more profit, otherwise, M's profit would decrease; 2) R's profit decreases, which increasingly deviates from the level under decentralized decision-making model of M's fairness neutrality. This shows that once M has the tendency of fairness concerns, regardless of whether M is concerned about the acquisition of own interests or the fairness of the profit distribution of the supply chain, R would make sacrifices to achieve the balance of the supply chain; 3) If R considers M's fairness concerns, the overall profit of the supply chain would not be affected; on the contrary, if R ignores M's fairness concerns, the system profit would decline as the degree of fairness concerns increases.

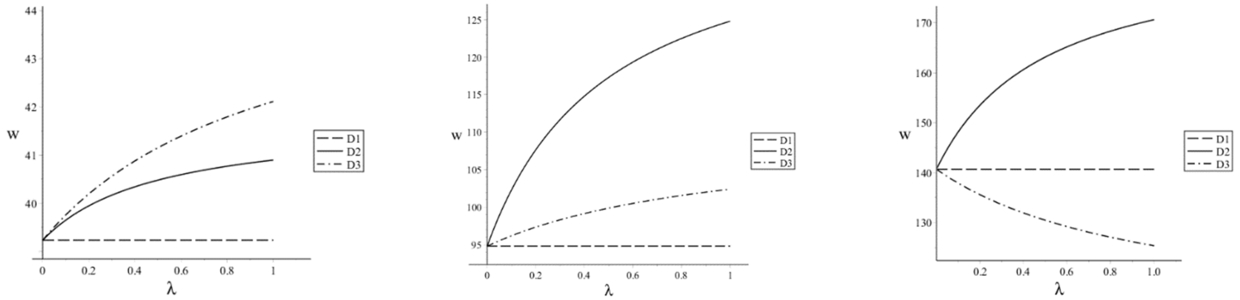
(5) Revenue sharing contract to coordinate green closed-loop supply chain

To verify whether the revenue-sharing contract can effectively coordinate the supply chain, numerical simulation is used to compare the results after coordination with the results before coordination. Assume that the values of the following parameters are: $a = 200$, $k = 500$, $c_m = 20$, $c_r = 16$, $\alpha = 4$, $\beta = 10$. The specific calculation results are shown in Table 3 and Table 4.

TABLE 3. Comparison of profits before and after the revenue sharing contract coordination for D2.

θ	λ_m	π_r^{D2*}	π_{rSC}^{C*}	π_m^{D2*}	π_{mSC}^{C*}
0.7	0.1	6271.12	9577.70	3990.71	4104.73
0.65	0.2	5863.90	8893.58	4397.93	4788.85
0.6	0.3	5558.49	8209.46	4703.34	5472.97
0.55	0.4	5320.95	7525.34	4940.88	6157.10
0.5	0.5	5130.91	6841.22	5130.91	6841.22
0.45	0.6	4975.43	6157.10	5286.10	7525.34
0.4	0.7	4845.86	5472.97	5415.96	8209.46
0.35	0.8	4736.23	4788.85	5525.60	8893.58

The above data in Table 3 and Table 4 show that the profits of R and M under the revenue-sharing contract are greater than the value before coordination. In other words, the revenue-sharing contract helps R and M to increase profits, and is effective for coordinating supply chain. When $\theta \in (0.35, 0.7)$, the revenue-sharing contract has a significant effect on D2 model. Similarly, when $\gamma \in (0.3, 0.7)$, the revenue-sharing contract has a significant effect on D3 model. The system profit of the supply chain has been improved, which indicates that the revenue-sharing contract is feasible when M has fairness concerns. In addition, according to the above tables, the revenue-sharing contract parameters are not only related to the bargaining power of both parties of the channel, but also related to the degree of M's fairness concerns.



(a) Low recycling difficulty and low greening efficiency **(b) High recycling difficulty and low greening efficiency** **(c) High greening efficiency**

FIGURE 3. The impact of fairness concerns on wholesale price.

(a) Low greening efficiency **(b) High greening efficiency**

FIGURE 4. The impact of fairness concerns on retail price.

TABLE 4. Comparison of profits before and after the revenue sharing contract coordination for D3.

γ	λ_m	π_r^{D3*}	π_{rSC}^{C*}	π_m^{D3*}	π_{mSC}^{C*}
0.7	0.1	6219.29	9577.70	3392.34	4104.73
0.65	0.2	5701.01	8893.58	3325.59	4788.85
0.6	0.3	5262.47	8209.46	3238.45	5472.97
0.55	0.4	4886.58	7525.34	3141.38	6157.10
0.5	0.5	4560.81	6841.22	3040.54	6841.22
0.45	0.6	4275.76	6157.10	2939.59	7525.34
0.4	0.7	4024.25	5472.97	2840.64	8209.46
0.35	0.8	3800.68	4788.85	2744.93	8893.58
0.3	0.9	3600.64	4104.73	2653.10	9577.70

VIII. CONCLUSION

This paper considers green closed-loop supply chain consisting of M and R, and discusses the impact of M's fairness concerns on supply chain by establishing centralized and decentralized decision model. Furthermore, a revenue-sharing contract is proposed to coordinate the supply chain. The study found that: 1) When R considers M's fairness concerns, wholesale price and M's profit increase and R's profit decreases with the increasing of fairness concerns, and recycling rate of waste product, product green degree, retail price, and market demand and the system profit are not affected by fairness concerns. M's fairness concerns behavior is beneficial to oneself but not to R; 2) When R ignores M's fairness concerns, the recycling rate of waste product, product green degree, market demand, the profits of both parties and the supply chain decrease with increasing of the degree of fairness concerns, wholesale price and retail price are related to fairness concerns and greening efficiency. M's fairness concerns behavior is detrimental to M, R, consumers and the ecological environment; 3) In decentralized decision-making model, the comparison of wholesale prices of M's fairness neutrality, R considering M's fairness concerns and R ignoring M's fairness concerns is related to the difficulty of recycling waste products and the greening efficiency of product; 4) The parameters of revenue-sharing contract can increase the profits of R and M within a certain value range, and alleviate the ''dual marginal effect'' of decentralized decision-making model; In addition, the effectiveness of revenue-sharing contract depends not only on the bargaining power of M and R, but also on M's fairness concerns.

This paper only deals with the pricing and coordination of green closed-loop supply chain. In the future, different power-led structure situations would be studied. In addition, this paper only considers the fairness concerns of manufacturer, in the future, the impact of other decision-makers' behavior and psychological tendencies on decision-making would be analyzed.

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APPENDIX

Proof of Property 1: $\frac{\partial w^{D2*}}{\partial \lambda_m} = \frac{a-c_m}{2(1+2\lambda_m)^2}$, because $a - c_m > 0$, $\frac{a-c_m}{2(1+2\lambda_m)^2} > 0$. $\tau^{D2*}, g^{D2*}, p^{D2*}$ and D^{D2*} are all independent functions of λ_m, therefore, the first derivative of λ_m is 0. Property 1 is proved.

Proof of Property 2: $\frac{\partial \pi_m^{D2*}}{\partial \lambda_m} = \frac{k(a-c_m)^2}{2(1+2\lambda_m)^2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\frac{\partial \pi_r^{D2*}}{\partial \lambda_m} = -\frac{k(a-c_m)^2}{2(1+2\lambda_m)^2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\frac{\partial u_m^{D2*}}{\partial \lambda_m} = \frac{k(a-c_m)^2}{4\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, because $k > \frac{(c_m-c_r)^2}{4-\alpha^2/\beta}$, and $\frac{\partial \pi_m^{D2*}}{\partial \lambda_m} > 0$, $\frac{\partial \pi_r^{D2*}}{\partial \lambda_m} < 0$, $\frac{\partial u_m^{D2*}}{\partial \lambda_m} > 0$ can be got; π_s^{D2*} is a function independent of λ_m, so the first derivative of λ_m is 0. Property 2 is proved.

Proof of Property 3: $\frac{\partial \tau^{D3*}}{\partial \lambda_m} = -\frac{(a-c_m)(c_m-c_r)}{2(1+\lambda_m)^2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\frac{\partial g^{D3*}}{\partial \lambda_m} = -\frac{k\alpha(a-c_m)}{2\beta(1+\lambda_m)^2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\frac{\partial D^{D3*}}{\partial \lambda_m} = -\frac{k(a-c_m)}{(1+\lambda_m)^2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, because $k > \frac{(c_m-c_r)^2}{4-\alpha^2/\beta}$, $a - c_m > 0$ and $c_m - c_r > 0$, then $\frac{\partial \tau^{D3*}}{\partial \lambda_m} < 0$, $\frac{\partial g^{D3*}}{\partial \lambda_m} < 0$, $\frac{\partial D^{D3*}}{\partial \lambda_m} < 0$ can be get. Property 3 is proved.

Proof of Property 4: $\frac{\partial w^{D3*}}{\partial \lambda_m} = \frac{k\left(2-\alpha^2/\beta\right)(a-c_m)}{2(1+2\lambda_m)^2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\frac{\partial p^{D3*}}{\partial \lambda_m} = \frac{k\left(2-\alpha^2/\beta\right)(a-c_m)}{2(1+2\lambda_m)^2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, when $0 < \frac{\alpha^2}{\beta} < 2$, there is $\frac{\partial w^{D3*}}{\partial \lambda_m} = \frac{\partial p^{D3*}}{\partial \lambda_m} > 0$; when $2 < \frac{\alpha^2}{\beta} < 4$, there is $\frac{\partial w^{D3*}}{\partial \lambda_m} = \frac{\partial p^{D3*}}{\partial \lambda_m} < 0$; when $\frac{\alpha^2}{\beta} = 2$, there is $\frac{\partial w^{D3*}}{\partial \lambda_m} = \frac{\partial p^{D3*}}{\partial \lambda_m} = 0$. Property 4 is proved.

Proof of Property 5: $\frac{\partial \pi_m^{D3*}}{\partial \lambda_m} = -\frac{k\lambda_m(a-c_m)^2}{2(1+\lambda_m)^3\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\frac{\partial \pi_r^{D3*}}{\partial \lambda_m} = -\frac{k(a-c_m)^2}{2(1+\lambda_m)^2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\frac{\partial \pi_s^{D3*}}{\partial \lambda_m} = -\frac{k(1+2\lambda_m)(a-c_m)^2}{2(1+\lambda_m)^3\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\frac{\partial u_m^{D3*}}{\partial \lambda_m} = -\frac{k(a-c_m)^2}{4(1+\lambda_m)^2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, because $k > \frac{(c_m-c_r)^2}{4-\alpha^2/\beta}$, there are $\frac{\partial \pi_m^{D3*}}{\partial \lambda_m} < 0$, $\frac{\partial \pi_r^{D3*}}{\partial \lambda_m} < 0$, $\frac{\partial \pi_s^{D3*}}{\partial \lambda_m} < 0$, $\frac{\partial u_m^{D3*}}{\partial \lambda_m} < 0$. Property 5 is proved.

Proof of Conclusion 1: $\pi_r^{D1*} = \frac{k(a-c_m)^2}{2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\pi_m^{D1*} = \frac{k(a-c_m)^2}{4\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, it is easy to see $\pi_r^{D1*} = 2\pi_m^{D1*}$. Conclusion 1 is proved.

Proof of Conclusion 2: $p^{D1*} = p^{D2*} = a + \frac{k\left(\alpha^2/\beta-2\right)(a-c_m)}{2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\Delta p^{23} = p^{D3*} - p^{D2*} = \frac{k\left(2-\alpha^2/\beta\right)(a-c_m)\lambda_m}{2(1+\lambda_m)\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\Delta p^{C1} = p^{D1*} - p^{C*} = \frac{k\left(2-\alpha^2/\beta\right)(a-c_m)}{2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$. Therefore, according to the scope of $\frac{\alpha^2}{\beta}$, Conclusion 2 can be got. Conclusion 2 was proved.

Proof of Conclusion 3: $\Delta w^{12} = w^{D2*} - w^{D1*} = \frac{(a-c_m)\lambda_m}{2+4\lambda_m} > 0$, $\Delta w^{13} = w^{D3*} - w^{D1*} = \frac{k\left(2-\alpha^2/\beta\right)(a-c_m)\lambda_m}{2(1+\lambda_m)\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\Delta w^{23} = w^{D3*} - w^{D2*} = \frac{\lambda_m(a-c_m)\left(\beta(c_m-c_r)^2(1+\lambda_m)-k\left(2\beta+\alpha^2\lambda_m\right)\right)}{2(1+\lambda_m)(1+2\lambda_m)\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$. When $0 < \frac{\alpha^2}{\beta} < 2$, there is $\Delta w^{13} > 0$; when $2 < \frac{\alpha^2}{\beta} < 4$, there is $\Delta w^{13} < 0$. When $\frac{(c_m-c_r)(a-c_r)}{4-\alpha^2/\beta} < k < \frac{\beta(c_m-c_r)^2(1+\lambda_m)}{2\beta+\alpha^2\lambda_m}$, there is $\Delta w^{23} > 0$, when $k > \frac{\beta(c_m-c_r)^2(1+\lambda_m)}{2\beta+\alpha^2\lambda_m}$, there is $\Delta w^{23} < 0$. Conclusion 3 is proved.

Proof of Conclusion 4: $\tau^{D1*} = \tau^{D2*} = \frac{(a-c_m)(c_m-c_r)}{2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)}$, $\Delta\tau^{23} = \tau^{D3*} - \tau^{D2*} = -\frac{(a-c_m)(c_m-c_r)\lambda_m}{2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)(1+\lambda_m)} < 0$, $\Delta\tau^{C1} = \tau^{D1*} - \tau^{C*} = -\frac{(a-c_m)(c_m-c_r)}{2\left(k\left(4-\alpha^2/\beta\right)-(c_m-c_r)^2\right)} < 0$, $\tau^{C*} > \tau^{D1*} = \tau^{D2*} > \tau^{D3*}$ can be got. Similarly, it can be proved that $g^{C*} > g^{D1*} = g^{D2*} > g^{D3*}$ and $D^{C*} > D^{D1*} = D^{D2*} > D^{D3*}$. Conclusion 4 is proved.

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