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# A Coordinated Revenue-Sharing-Based Pricing Decision Model for Remanufactured Products in Carbon Cap and Trade Regulated Closed-Loop Supply Chain

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**ABSTRACT** The pricing strategy of remanufactured products has been widely regarded as a significant issue due to the associated economic benefits for both suppliers and retailers awareness worldwide. However, the overall profit determined based on centralized pricing strategy or decentralized pricing strategy is not in line with the actual profit of the manufacturer and the retailer, especially when taking the cost of carbon emission under the system of cap and trade into account. This paper proposes a revenue sharing contract model to coordinate the optimal pricing strategies for both manufacturers and retailers who engages in remanufacturing. The model considers the different Willingness to Pay (WTP) for remanufactured products, and profit distribution of manufacturers and retailers under the Cap and Trade policy. The optimal retail and wholesale price of new products and remanufactured products are derived by solving a convex programming model. Our results identify that: (1) The carbon emission cap is negatively correlated with the retail price of both new products and remanufactured products when the established profits function of the closed-loop supply chain is set to be a constant. The retail price of remanufactured products is also negatively correlated with the value of WTP, while the retail price of new products is positively correlated with WTP. (2) The profit of retailers is positively correlated with carbon emission cap, while the relation of the manufacturer's profit and carbon limit present an inverted U shape, which indicates the optimal carbon emission limit for manufacturers achieving the maximum profit. Moreover, the profit of the retailer and manufacturer and the coefficient of WTP is positively correlated. Numerical experiments are conducted to examine the feasibility of the proposed pricing strategies and gain optimal managerial insights for carbon cap and trade policy.

**INDEX TERMS** Closed-loop supply chain, remanufactured products, revenue-sharing pricing model, carbon emission, cap and trade policy.

## I. INTRODUCTION

Remanufactured products have been arisen the interests from both the governmental regulation and supply chain management since reverse logistics significantly reduced residual wastes by providing customers abundant of qualified re-products in a lower cost during the recent decades. On the other hand, in order to mitigate the overall carbon emission in the closed-loop supply chain, Carbon Cap and Trade police, a cooperative government and market-based system, is designed to control energy consumption that allows corporations to trade carbon emissions allowances under a total government issued cap, or limit, on those emissions. Government policies, such as the EU Emissions Trading Directive in 2003, which were issued to set the carbon emission limit, and has also been demonstrated to be relevant to the gross revenue of manufacturers and retailers and extent of customer's willing to pay (WTP) [1]. Therefore, it is significant

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to explore the impact of Carbon Cap and Trade policy on manufacturers and retailers offering new and remanufactured products in different strategy to the pricing decision.

The effect of pricing strategy on the coordination and stability of closed-loop supply chain system has been studied quite extensively. In the previous studies, most of the pricing strategies of the closed-loop supply chain is established based on centralized decision model and decentralized decision model [2], [3]. Decentralized decision model is defined as that manufacturers and retailers determine the pricing strategy respectively from the perspective of each side in order to obtain the maximum wholesale or retail payoff. However, the overall profit regarding to the supply chain are ignored with this decentralized decision model [4]. Centralized decision model determines the products' price cooperatively by manufacturers and retailers, in order to reduce the decision cost and achieve the maximum profits for both the manufacture and retail industry. However, it can bring about risks such as bottlenecks caused by increased layers of agreements and slower decision process in most practical usage [5]. A revenue-sharing contract model is established to make the total profit of the supply chain under decentralized decision model as same as the centralized decision model, through the manufacturer's lowest wholesale price to the retailer and retailers give certain retail profits to manufacturers [6].

This article sets the profit function of manufacturers and retailers under the Cap and trade system by considering the different WTP for remanufactured products, and finds the optimal retail price and wholesale price of new products and remanufactured products according to the setting of total recycle costs and the reference of demand functions considering WTP in assumptions, and then get the best profit through the inverse method. The results show that the total profit and pricing strategy of the centralized decision model is better than the decentralized decision model. Therefore, we establish a revenue sharing contract model to coordinate the effect of making the total profit of the decentralized decision model to a centralized decision. The main contributions of this paper are as follows:

(1) In this paper, the optimal pricing decision model is established by considering the carbon emission limit in a closed-loop supply chain. The study finds that there exists an optimal carbon emission limit to maximize the profit of the closed-loop supply chain, and provide a reference for manufacturers who need to control carbon emissions to set reasonable wholesale prices. In previous studies, the production cost of new products was not much different from the recycling and remanufacturing costs of remanufactured products because of the carbon emission limit was not considered. Therefore, the sales prices of new products and remanufactured products in the market are not much different. Then the customer's willingness to pay for remanufactured products is reduced, and sales of new products are increased, resulting in an increase in the total cost of the closed-loop supply chain.

(2) This paper considers the customer's willingness to pay for remanufactured products when establishing the optimal pricing decision model. Studies have shown that if the customer's willingness to pay for remanufactured products is higher, the retail price of the remanufactured product is higher, and the overall profit of the closed-loop supply chain is higher. In previous studies, the willingness to pay for remanufactured products was not considered in pricing strategy of closed-loop supply chain, and manufacturers did not know the market demand for new and remanufactured products. If too many remanufactured products were produced while customers were more inclined to buy new products, those remanufactured products may become slow-moving products, which will cause a large amount of waste of resources.

(3) This paper establishes a revenue sharing contract model. Through introducing a contract parameter, manufacturers and retailers can negotiate the decision on the pricing of new products and remanufactured products, so that the overall benefit of the closed-loop supply chain can be maximized. In previous studies, the revenue-sharing contract model has been applied in various supply chains, but these studies didn't solve the problem of the impact with consumers' WTP on product pricing and overall profit in the closed-loop supply chain under the carbon cap and trade regulations.

The remainder of this paper is organized as follows. The state of the art on the pricing strategies of closed-loop supply chain are summarized in Section 2, problems statement and proposed relevant assumptions are described in Section 3. And in section 4, a set of pricing model and profits models of the closed-loop supply chain are established and illustrated. Our comparative analysis and conclusions are respectively included in Section 5 and Section 6.

## II. LITERATURE REVIEW

This section summarizes the state of the art related to pricing decision models applied for remanufactured products, and sorts out several comparative analyses in terms of the impact of Cap and Trade police on profits of closed-loop supply chain, which are subsequently detailed in Section A and B respectively.

### A. RESEARCH ON PRICING STRATEGY OF CLOSED-LOOP SUPPLY CHAIN

Pricing decisions affect the profitability of manufacturers and retailers even the entire closed-loop supply chain. Therefore, the study of pricing strategy has become an important research perspective in the closed-loop supply chain. There is some literature on product pricing from the perspective of recycling products in the process of reverse logistics, considering the impact of recycling costs [7], [8]. Modak *et al.* studied the pricing strategy of the closed-loop supply chain from the perspective of recycling and product quality level, and analyzed the impact of the recycling of waste materials from three different recyclers on product pricing [7]. Zhu *et al.* studied the environmentally friendly disposal and effective recycling and considered the impact of consumer behavior on the electrical recovery of waste electrical [8].

The impact of product pricing on the sales channels of products and the recycling channels of discarded products of closed-loop supply chain has also received some attention [9]–[13]. For example, Giri *et al*. studies the pricing strategy of supply chain and return product collection decisions in two different sales and recycling channels in five different scenarios, include centralized, decentralized, and manufacturer-led, retailer-led and third party-led decentralized scenarios [9]. He *et al*. studied the different sales channels of new and remanufactured products and explores pricing decisions of closed-loop supply chain and government's subsidy policy by competing for new and remanufactured products [10].

These studies focus on the pricing strategy problems of the closed-loop supply chain, but they did not consider carbon emission and WTP will also affect the pricing strategy and the profit of closed-loop supply chain. There is a significant difference in consumers' willingness to pay for remanufactured products and new products and has a significant impact on manufacturers' decisions [14]. Therefore, from the perspective of consumers, some researchers studied the influencing factors and extent of WTP of remanufactured products from different perspectives, including guarantee strength and ambiguity tolerance, quality perception, remanufacturing process and clarity of ideas [15]–[19]. Through the analysis of the above documents, it can be found that the driving factors affecting consumers' WTP of remanufactured products not only the objective factors caused by the particularity of the remanufactured products, but also the behavioral factors of consumers. Atasu *et al*. constructed a remanufacturing closed-loop supply chain system based on WTP differentiation, and studied the cost advantages of original equipment manufacturers for remanufacturing and remanufacturing, consumer awareness of remanufactured products, and market demand relationships [20]. Fewer *et al*. extended the literature [20] to construct a remanufacturing closed-loop supply chain system consisting of a single manufacturer and a demand market, and obtained the relationships of a function between the demand for new products and remanufactured products and the sales price [21]. The results show that consumers have different WTP preferences for new products and remanufactured products, and studied the relevant decision-making issues when the two products are differentially priced. However, the above studies did not provide a good analysis of the impact of WTP on product pricing and the profitability of the closed-loop supply chain, and not considering the carbon emission limit of the product at the same time would also affect the pricing of remanufactured products.

### B. RESEARCH ON CAP AND TRADE POLICE

Increased global warming and various pollutant emissions have led countries to implement various measures, from increasing taxes, issuing operating permits and voluntary emission reduction incentives to the necessary regulatory policies [22]. Given this environment, a lot of research on the cap and trade system is presented to everyone. Behnam *et al*. proposed an optimization model for balancing the supply chain carbon footprint and tactical economic goals by considering carbon pricing [22]. The effects of carbon pricing in the closed-loop supply chain are analyzed through specific examples. Li *et al*. analyzed the impact of carbon subsidies on the profit and carbon emissions of the forward supply chain, the remanufactured closed-loop supply chain and the carbon-subsidized remanufactured closed-loop supply chain. It also discussed when and how the government should implement carbon subsidy policies to encourage companies to reduce carbon emissions [23]. Du *et al*. examines a supply chain consisting of carbon-dependent manufacturers and suppliers with a single emission permit, where emissions permits become necessary for production. The effects of carbon footprint and low carbon preference on enterprise production decisions in cap-and-trade systems were also studied [24], [25]. Chang *et al*. studied a monopoly enterprise that produces new products and remanufactured products. Two profit maximization models were established for independent demand market and alternative demand market, and carbon emission limits and trading mechanisms were considered [26]. However, the above researches did not consider that carbon emissions not only have an impact on the production decisions of products in the supply chain, but also on the pricing of products. Turki *et al*. constructed two models determined the optimal manufacturing cycle length and available inventory capacity for new manufacturing and remanufacturing projects by considering carbon emissions. In addition, the impact of carbon emission limits, carbon trading prices and return supply percentages on carbon emissions is also analyzed [27]. However, in the above research on the Cap and Trade police, there is almost no pricing research on the closed-loop supply chain, while our product pricing is often affected by the carbon emission limit and the carbon trading price.

According to the above-mentioned literature we can see, there are many researches on pricing strategy of closed-loop supply chain from a different perspective. However, there is no studies to established a revenue-sharing contract model under the Cap and trade system and considering the consumers' differentiation WTP. Therefore, this article established an optimal pricing model through sets the profit function of manufacturers and retailers under the Cap and trade system by considering the different willingness to pay for remanufactured products, then the results clearly show the impact of carbon emission limits and customers' willingness to pay on product prices and profits through numerical simulation.

## III. PROBLEM DESCRIPTION AND ASSUMPTIONS

### A. PROBLEM DESCRIPTION

In this section, the overall schematic of closed-loop supply chain system is presented, as shown in Figure 1, where of the problems of modelling optimal pricing strategy for manufacturers and retailers regarding the re-products in reverse logistics and forward logistics are explicitly described and

**TABLE 1.** Symbol description.

| Symbol | Description |
|---|---|
| $c_n, c_r$ | Unit production cost of new products $c_n$ and remanufactured products $c_r$, we set $c_n > c_r > 0$. |
| $q_n, q_r$ | The quantity of new products $q_n$ and remanufactured products $q_r$ determined by the manufacturer according to their production plan. |
| $q_r'$ | The quantity of recycled products determined by manufacturers. |
| $e_n, e_r$ | The carbon emission in process of producing new and remanufactured products, we set $e_n > e_r > 0$. |
| $p_n, p_r$ | The retail price of new products $p_n$ and remanufactured products $p_r$. |
| $w_n, w_r$ | The wholesale price of new products $w_n$ and remanufactured products $w_r$. |
| $\Pi_r, \Pi_m$ | The profit of retailers and manufacturers. |
| $p_e$ | The price of carbon trading between manufacturers. |
| $\Pi_h$ | The profit of the entire supply chain. |
| $\tau$ | The ratio of recycled products $q_r'$ to the total quantity of products $q_n + q_r$ determined by manufacturers, which is presented as $\tau = \frac{q_r'}{q_n+q_r}$. In this paper, we set $\tau \in (0, 1)$. |
| $\theta$ | The ratio of remanufacturer determined re-products $q_r$ to the quantity of recycled products $q_r'$, which is presented as $\theta = \frac{q_r}{q_r'}$. |
| $A$ | The unit recovery price of the discarded product. |
| $B$ | Scale parameter $B$ presents the positive relation with the fixed investment invested by the manufacturer by giving condition of certain recovery rate $\tau$. |
| $\beta$ | Coefficient of customers' willing to pay (WTP) remanufactured products, we set $\beta \in (0, 1)$. |
| Q | The market capacity Q is an estimated parameter reflecting the total demand of new products and remanufactured products. |
| $G$ | The maximum carbon emission allowed in the closed-loop supply chain. |
| $\lambda$ | The Lagrangian coefficient is a certain constant transferring conditional extreme value problem into an unconditional extreme value problem， we set $\lambda > 0$. |

defined in following part. Moreover, several factors, i.e. carbon cap and trade regulations, customers' willing to pay remanufactured products, recovery rate and cost recovery are considered as constraint conditions related to modelling of optimal pricing. It is also should be noted that, all notations throughout the modelling process of this work are summarized in Table 1.

In the reverse logistics of the closed-loop supply chain, the manufacturer will recycle the used products from consumers in terms of the unit recycling cost A. Then remanufacture it to a state like the new product. In reverse logistics, it is necessary to consider the recovery rate $\tau$ of used products, since when the recovery rate $\tau$ is higher, the degree of loss of the product is lower, which means the lower the cost of remanufacturing, so the recycling rate of the used product should be considered in the reverse logistics. In the forward logistics of the closed-loop supply chain, the manufacture sales the new and remanufactured products to the retailer at wholesale price $w_n$, $w_r$, then the retailer sales the products to the consumer at retail price $p_n$, $p_r$. In the forward logistics, the unit's production cost per unit of production of new products is $c_n$, and the carbon emissions per production of a new product are $e_n$. The unit's production cost for the manufacturer to renovate the used product into a new product is $c_r$, and the carbon emissions generated are $e_r$. Among them, the production cost of new products and the carbon emissions during production are higher than those of remanufactured products. Since the government controls the company's carbon emission limit $G$,

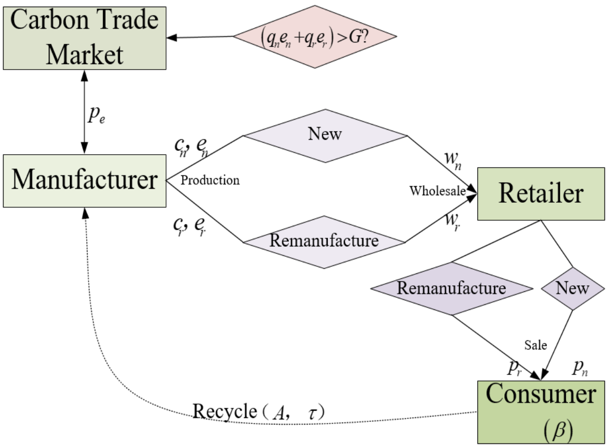



**FIGURE 1.** Structural model of a closed-loop supply chain.

manufacturers must buy and sell carbon emissions (The carbon trading price is $p_e$) according to their own needs to achieve production demand or obtain greater profits. If the carbon emissions from the production of new and remanufactured products exceed the government's maximum carbon emission limit, manufacturers will have to spend more money to purchase carbon emissions from the carbon trading market to meet their own production needs; If the carbon emissions do not exceed the maximum carbon emission limit, the manufacturer can sell excess carbon emissions to other companies, which will generate a certain profit. The above-mentioned unit production costs, carbon emissions, costs or profits from carbon trading will affect the wholesale price of the products, and the factors determining the retail price of the products are the wholesale price and the WTP, which is presented as $\beta$. Consumers' willingness to pay affects the retail price of the product, which affects the profitability of the entire closed-loop supply chain.

### B. ASSUMPTIONS

Manufacturers and retailers are independent decision makers, manufacturers are considered as leaders in the Stackelberg game model and retailers are considered as followers in the closed-loop supply chain [12]. Since remanufactured products and new products have the same functional nature, one consumer only purchases a single type of product in the market demand [28], [29]. We assume that we fully understand all the information about the carbon limit and the carbon trading market. Under the cap and trade system, the government allows the maximum carbon emission in the supply chain is $G$, and manufacturers can buy and sell carbon emission limit according to their own needs to achieve production demand, in which the carbon trading price is $p_e = a - bG$. Where $a, b$ is carbon emissions trading price coefficient. The linear relationship between carbon trading prices and carbon emissions.

We assume that the proportion of manufacturers recycling old products to market demand is $\tau$, of which $0 < \tau < 1$. The larger the value of $\tau$ is, the higher the proportion of remanufactured products is. And manufacturers can save energy and reduce carbon emissions and increase profits, which is beneficial to promote the implementation of remanufacturing closed-loop supply chain. In the closed-loop supply chain, the fixed investment of recycling discarded products and the total cost of recycling are

$$I(\tau) = B\tau^2 \tag{1}$$

$$C(\tau) = B\tau^2 + A\tau\,(q_n + q_r) \tag{2}$$

In the function, we make the investment scale parameter $B > 0$, $A$ is the recovery price of one discarded product and $q_n, q_r$ is market demand for new products and remanufactured products. To make the study meaningful, we assume that

$$A < \frac{Q(1-(1-\beta)\tau)-(c_n-(c_n-c_r)\tau)-p_e(e_n-(e_n-e_r)\tau)}{\tau} \tag{3}$$

The condition (3) is to meet the positive needs of remanufactured products which means the quantity of remanufactured products must be greater than zero. And the recycling price of the discarded product cannot be too high, otherwise the manufacturer will not recycle the old product. Then we assume the consumers have different willingness to pay for remanufactured products. The consumer preference coefficient of remanufactured products is $\beta$, $\beta$ is changed between 0 to 1. Assume that the market capacity is $Q$, the demand functions for new and remanufactured products are $p_n = Q - q_n - \beta q_r$ and $p_r = \beta\,(Q - q_r - q_n)$, that the relevant proof is shown in the appendix. Based on the above demand function, we use Mathematica software to calculate and simplify, then we can get:

$$q_n = \frac{p_r - p_n + Q(1-\beta)}{1-\beta} \tag{4}$$

$$q_r = \frac{p_n\beta - p_r}{\beta(1-\beta)} \tag{5}$$

## IV. METHODOLOGY

In this section, a Revenue-sharing contract model is established to optimize the decentralized decision model by constructing a coefficient correlated with the revenue-sharing ratio of manufacturer with retailer to make the total profit of the supply chain under decentralized decision equal to the total profit under centralized decision, as shown in Fig. 2. Firstly, the overall revenue model of close-loop supply chain is separately estimated by decentralized decision model considering remanufacturer's profit with the carbon cap and trade and recycling cost, as well as the and retailer's profit based on remanufacturer's wholesale price. Then, a factor of collaborating remanufacturer and retailer for negotiating wholesale and retail products pricing strategy and sharing the revenue for both is specifically integrated with the decentralized decision model. Finally, the optimal pricing strategy for wholesale and retail products are induced to improve the overall profit of closed-loop supply chain to the maximum for both of manufacturer and retailer.

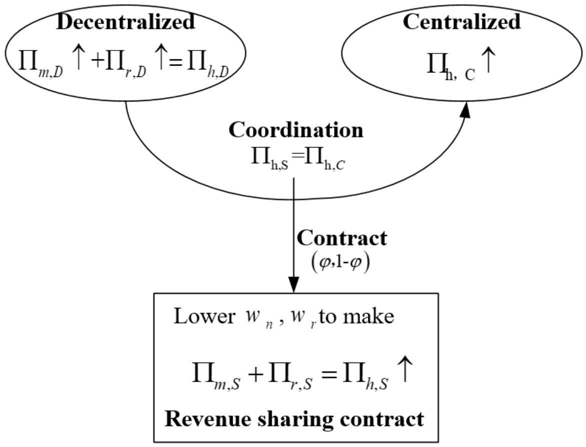



**FIGURE 2.** **Schematic of Revenue-sharing contract model.**

Where $\Pi_{r,D}$ and $\Pi_{m,D}$ is the retailer and manufacturer's profit under the decentralized decision model, $\Pi_{h,D}$ is the total profit of the closed-loop supply chain under decentralized decision model. $\Pi_{h,C}$ is defined as the entire supply chain profit under the centralized decision model. And $\varphi$ is revenue shared contract parameters, $\Pi_{r,S}$ and $\Pi_{m,S}$ denotes the profit of retailers and manufacturers under revenue-sharing contract model, $\Pi_{h,S}$ is defined as the entire supply chain profit under revenue-sharing contract model. Where $\uparrow$ means that the objective function is maximized.

### A. DECENTRALIZED DECISION MODEL

The retailer's general profit in the mode of the decentralized decision strategy is defined by the following formula:

$$\Pi_{r,D} = (p_n - w_n)\, q_n + (p_r - w_r)\, q_r \tag{6}$$

where $\Pi_{r,D}$ is the retailer's overall profit.

The Hessian matrix of the manufacturer's profit function can be obtained according to formula (6).

$$H = \begin{Bmatrix} \frac{2}{\beta - 1} & \frac{2}{1-\beta} \\ \frac{2}{1-\beta} & \frac{2}{\beta(\beta - 1)} \end{Bmatrix}, \quad which\ \frac{2}{\beta - 1} < 0;$$
$$|H| = \frac{4}{\beta(1-\beta)} > 0$$

where $H$ is Hessian matrix and $|H|$ is the value of the Hessian matrix.

It can see that the retailer's profit function Hessian matrix is a negative fixed matrix, and there has the best retail price maximizes the retailer's profit.

According to the equation (4), (5), and considering the first-order partial derivative of equation (6), the retailer's response function is: $p_n = \frac{w_n+Q}{2}, p_r = \frac{w_r+Q\beta}{2}$.

The manufacturer's profit function is:

$$\Pi_{m,D} = (w_n q_n + w_r q_r) - (c_n q_n + c_r q_r) - (B\tau^2 + A\tau(q_n + q_r)) - p_e(e_n q_n + e_r q_r - G) \quad s.t. \tau(q_n + q_r) > q_r \tag{7}$$

$\Pi_{m,D}$ is the manufacturer's profit under the decentralized decision model. The manufacturer determines the certain quantity of the new products $q_n$ and the remanufactured products $q_r$ in production plan according to the market demand of the product, while also determines how many amount of discarded products $q_r^{'}$ should be reasonably recycled, which have been described in Table 1. In this paper, we define the recycling ratio of discarded products as $\tau = \frac{q_r^{'}}{q_n+q_r}$, which presents the ratio of recycled discarded products to the total number of products ($q_n + q_r$, the sum of new products and remanufactured products) that the manufacturer plans to produce. It should be noted that, we set $\tau \in (0, 1)$ in order to avoid excessive recycling costs if over recycling discarded products. Furthermore, we define the ratio of remanufactured products with the recycled products as $\theta = \frac{q_r}{q_r^{'}}$, which presents the proportion of how many recycled products $q_r^{'}$ can be effectively transformed to be remanufactured products $q_r$ for further sale to customers, therefore, it exists $q_r^{'} > q_r$ and $\theta \in (0, 1)$. Consequently, the restriction condition $\tau(q_n + q_r) > q_r$ represents that the quantity of the remanufactured products $q_r$ determined by manufacturer is less than the amount of recycled products $q_r^{'}$, so as to in line with the reality.

The Hessian matrix of the manufacturer's profit function can be obtained according to formula (7).

$$H = \begin{Bmatrix} \frac{1}{\beta - 1} & \frac{1}{1-\beta} \\ \frac{1}{1-\beta} & \frac{1}{\beta(\beta-1)} \end{Bmatrix}, \quad which\ \frac{1}{\beta - 1} < 0;$$
$$|H| = \frac{1}{\beta(1-\beta)} > 0$$

We can see that the Hessian matrix of the manufacturer's profit function is a negative fixed matrix. Therefore, there is optimal value of wholesale price strategy existed for the new products and remanufactured products to obtain the manufacturer's profit to the maximum by searching the solutions of $w_{n,D}^*$ and $w_{r,D}^*$ in Equation 7, which in turn, the first-order partial derivative of Equation 7 equal to zero. More detailed process is as follows:

First, we construct a cost function (8) to resolve the optimal value of equation 7 by Lagrangian multiplier to consider the restriction of $\tau(q_n + q_r) > q_r$ into the profit function of manufacturer, where $\lambda$ is the Lagrangian coefficient is a certain constant transferring conditional extreme value problem into an unconditional extreme value problem, we set $\lambda > 0$ to make the constraint $\tau(q_n + q_r) > q_r$ have a positive impact on the profit function.

$$\Pi_{m,D}^{'} = (w_n - c_n)\, q_n + (w_r - c_r)\, q_r - B\tau^2 - A\tau(q_n + q_r) - p_e(e_n q_n + e_r q_r - G) + \lambda(\tau(q_n + q_r) - q_r) \tag{8}$$

Then substitute $q_n = \frac{p_r - p_n + Q(1-\beta)}{1-\beta}, q_r = \frac{p_n\beta - p_r}{\beta(1-\beta)}, p_n = \frac{w_n+Q}{2}, p_r = \frac{w_r+Q\beta}{2}$ into the equation (8), the equation (9)

$$w_{n,D}^{*} = \frac{-Q(\beta\tau(2-\beta\tau)+(1-\tau)^2)+(1-(1-\beta)\tau)((c_n-c_r)\tau-c_n+p_e((e_n-e_r)\tau-e_n)-A\tau)}{-2+4(1-\beta)\tau-2(1-\beta)\tau^2} \tag{10}$$

$$w_{r,D}^{*} = \frac{\beta(Q(-1+(1-\beta)(3-2\tau)\tau))+((c_n-c_r)\tau-c_n)+p_e((e_n-e_r)\tau-e_n)-A\tau}{-2+4(1-\beta)\tau-2(1-\beta)\tau^2} \tag{11}$$

$$p_{n,D}^{*} = \frac{Q\left(-3+6\tau(1-\beta)-(1-\beta)(3+\beta)\tau^2\right)-(-1+(1-\beta)\tau)((c_n-c_r)\tau-c_n+p_e((e_n-e_r)\tau-e_n)-A\tau)}{-4+8(1-\beta)\tau-4(1-\beta)\tau^2} \tag{12}$$

$$p_{r,D}^{*} = \frac{\beta(Q(-3+7\tau(1-\beta)-4\tau^2(1-\beta))-4\tau^2(1-\beta))+(c_n-c_r)\tau-c_n)+p_e((e_n-e_r)\tau-e_n)-A\tau)}{-4+8(1-\beta)\tau-4(1-\beta)\tau^2} \tag{13}$$

$$q_{n,D}^{*} = \frac{Q(-1+(2-\beta)\tau+\tau^2(\beta-1))+(1-\tau)(c_n-(c_n-c_r)\tau)+p_e(1-\tau)((e_n-(e_n-e_r)\tau)+(1-\tau)A\tau)}{-4+8(1-\beta)\tau-4(1-\beta)\tau^2} \tag{14}$$

$$q_{r,D}^{*} = \frac{\tau(Q(-1+(1-\beta)\tau)+c_n-(c_n-c_r)\tau+p_e(e_n-(e_n-e_r)\tau)+A\tau)}{-4+8(1-\beta)\tau-4(1-\beta)\tau^2} \tag{15}$$

$$\begin{aligned}\Pi_{m,D}^{*} = {} & \frac{-2Q(1-\beta)\tau^2(c_n-c_r+p_e(e_n-e_r))+p_e^2\tau^2(e_n-e_r)^2+2Ap_e(e_n-(e_n-e_r)\tau)+8Gp_e((1-\beta)(1+\tau)^2+\beta)}{8((1-\beta)(1-\tau)^2+\beta)} \\ & +\frac{8B(1-\beta)\tau^3(2-\tau)+(A^2-8B)\tau^2+Q(1-(1-\beta)\tau)(Q(1-(1-\beta)\tau)-2A\tau)+\tau^2(c_n-c_r)(c_n-c_r)(1+2p)-2A)}{8((1-\beta)(1-\tau)^2+\beta)} \\ & +\frac{2p_e\tau^2(c_n-c_r)(e_n-e_r-(c_n-c_r))+(1-2\tau)(c_n^2+e_n^2p_e^2)-32Gp_e(1-\beta)\tau-2(c_r+e_rp_e)Q\tau+2e_np_e(c_r+e_rp_e)\tau}{8((1-\beta)(1-\tau)^2+\beta)} \\ & +\frac{2c_n(A+c_r+e_rp_e)\tau-2e_np_eQ(1-(2-\beta)\tau)+2c_ne_np_e(1-2\tau)-2c_nQ(1-(2-\beta)\tau)}{8((1-\beta)(1-\tau)^2+\beta)}\end{aligned} \tag{16}$$

$$\Pi_{r,D}^{*} = \frac{(c_n-Q(1-\tau(1-\beta))+A\tau-(c_n-c_r)\tau-p_e\tau(e_n-e_r)+e_nM)^2}{16((1-\beta)(1-\tau)^2+\beta)} \tag{17}$$

is obtained.

$$\begin{aligned}&\Pi_{m,D}'' \\ &= (w_n-c_n)\left(\frac{Q-w_n+w_r-Q\beta}{2-2\beta}\right)+(w_r-c_r)\left(\frac{w_r-w_n\beta}{2(-1+\beta)\beta}\right) \\ &\quad -B\tau^2-A\tau\left(\frac{Q-w_n+w_r-Q\beta}{2-2\beta}+\frac{w_r-w_n\beta}{2(-1+\beta)\beta}\right) \\ &\quad -\left(e_n\left(\frac{Q-w_n+w_r-Q\beta}{2-2\beta}\right)+e_r\left(\frac{w_r-w_n\beta}{2(-1+\beta)\beta}\right)-G\right)p_e \\ &\quad +\lambda\left(\tau\left(\frac{Q-w_n+w_r-Q\beta}{2-2\beta}+\frac{w_r-w_n\beta}{2(-1+\beta)\beta}\right)-\frac{w_r-w_n\beta}{2(-1+\beta)\beta}\right)\end{aligned} \tag{9}$$

Finally, Let $w_n, w_r, \lambda$ in the formula (9) find the first-order partial derivative and make the partial derivative equal to $0.w_{n,D}^{*}, w_{r,D}^{*}$ is obtained by calculation in (10) and (11), as shown at the top of this page, where $w_{n,D}^{*}$ and $w_{r,D}^{*}$ is the best wholesale price of new product and remanufactured product.

By substituting the manufacturer's optimal wholesale price into the retailer's response function, the retail price of the retailer's new and remanufactured products is given in (12) and (13), as shown at the top of this page, where $p_{n,D}^{*}$ and $p_{r,D}^{*}$ denotes the best retail price of new products and remanufactured products.

Then we put $p_{n,D}^{*}, p_{r,D}^{*}$ into equation $q_n = \frac{p_r-p_n+Q(1-\beta)}{1-\beta}$, $q_r = \frac{p_n\beta-p_r}{\beta(1-\beta)}$, and we can get (14) and (15), as shown at the top of this page, where $q_{n,D}^{*}$ and $q_{r,D}^{*}$ is maximum market demand for new products and remanufactured products.

According to the equation (15), we can prove the condition (3) is reasonable.

Now we need to make sure:$q_{r,D}^{*} > 0$

However, $-4+8(1-\beta)\tau-4(1-\beta)\tau^2 = -4+4\tau(1-\beta)(2-\tau) < 0$

Therefore, $Q(-1+(1-\beta)\tau)+c_n-(c_n-c_r)\tau+p_e(e_n-(e_n-e_r)\tau)+A\tau < 0$

Then we can get:

$$A < \frac{Q(1-(1-\beta)\tau)-(c_n-(c_n-c_r)\tau)-p_e(e_n-(e_n-e_r)\tau)}{\tau}$$

The condition (3) can be proved.

Finally, the optimal profit of the manufacturer and retailer is calculated. Equations (16) and (17) show the value of $\Pi_{m,D}^{*}$ and $\Pi_{r,D}^{*}$, respectively, as shown at the top of this page, where $\Pi_{m,D}^{*}$ is the manufacturer's best profit under the decentralized decision model; $\Pi_{r,D}^{*}$ is the retailer's best profit under the decentralized decision model.

Therefore, the total profit of the closed-loop supply chain is:

$$\Pi_{h,D}^{*} = \Pi_{m,D}^{*} + \Pi_{r,D}^{*} \tag{18}$$

where $\Pi^*_{h,D}$ is the total profit of the closed-loop supply chain under decentralized decision model.

Analyze the above results and get the following conclusions:

*Proposition 1:* In decentralized decision model, $w_n$ and $p_n$ is negatively correlated with $\beta$. $w_r$ and $p_r$ is positively correlated with $\beta$.

This proposition states that the wholesale price and retail price of new products are affected by the coefficient of WTP, which the wholesale price and retail price of new products decreases with the coefficient of WTP increases; while the price of remanufactured products is reversed. When $\beta = 1$, we have $w^*_{n,D} = w^*_{r,D}, p^*_{n,D} = p^*_{r,D}$, which means when consumers have the same willingness to pay for these two types of products, the wholesale price and retail price of new products and remanufactured products are the same.

*Proposition 2:* Under the decentralized decision model, $w_n$, $w_r$ and $p_n, p_r$ are negatively correlated with $G$.

This proposition states that the carbon emission limits set by the government will affect the wholesale and retail prices of the products. As the carbon emission limit increases, the wholesale and retail prices of products decrease. The government should appropriately increase the carbon limit according to the specific situation, reduce the production cost of the manufacturer, and promote the sales of the product to a certain extent.

### B. CENTRALIZED DECISION MODEL

Under the decentralized decision model, the manufacturer and the retailer jointly determine the retail price of the product, regardless of the wholesale price, and only consider the overall benefit maximization. Therefore, the entire supply chain profit is:

$$\Pi_{h,C} = (p_n - c_n) q_n + (p_r - c_r) q_r - B\tau^2 - A\tau (q_n + q_r) \\ -p_e (e_n q_n + e_r q_r - G) \quad s.t.\tau(q_n + q_r) > q_r \quad (19)$$

where $\Pi_{h,C}$ is the entire supply chain profit under the centralized decision model under centralized decision model.

The Hessian matrix of the entire supply chain's profit function can be obtained according to formula (19).

$$H = \begin{Bmatrix} \frac{2}{\beta - 1} & \frac{2}{1-\beta} \\ \frac{2}{1-\beta} & \frac{2}{\beta(\beta-1)} \end{Bmatrix}, \quad which \ \frac{2}{\beta - 1} < 0;$$

$$|H| = \frac{4}{\beta(1-\beta)} > 0$$

Therefore, the Hessian matrix with the supply chain profit function is the negative fixed matrix, and the optimal retail price makes the overall supply chain profit reach the maximum. According to the equation (4), (5), and consider the first-order partial derivative of equation (19), we can get (20) and (21), as shown at the bottom of this page.

According to equation (19)-(21), we can get the optimal profit of the total supply chain in (22), as shown at the bottom of this page.

Analyze the above results and get the following conclusions:

*Proposition 3:* $\Pi^*_{h,C} > \Pi^*_{h,D}$

This proposition shows that centralized decision model is more efficient than decentralized decision model, making the overall profit of the closed-loop supply chain higher. Therefore, this paper designs a revenue sharing coordination decentralized closed-loop supply chain decision model.

*Proposition 4:* In centralized decision model, $p_n$ is negatively correlated with $\beta$, and $p_r$ is positively correlated with $\beta$.

This proposition states that the retail price of new products is affected by the value of WTP, which decreases as the coefficient of WTP increases. While the retail price of remanufactured products is reversed, the retail price of remanufactured products increased with the coefficient of WTP increased.

*Proposition 5:* Under the centralized decision model, $p_n$ and $p_r$ are negatively correlated with $G$.

$$p^*_{n,C} = \frac{Q(-1+\tau(1-\beta)(2-\tau(1+\beta))) + (1-(1-\beta)\tau)((c_n - c_r)\tau - c_n + p_e((e_n - e_r)\tau - e_n) - A\tau)}{-2 + 4(1-\beta)\tau - 2(1-\beta)\tau^2} \quad (20)$$

$$p^*_{r,C} = \frac{\beta(Q(-1+\tau(1-\beta)(3-2\tau)) + (c_n - c_r)\tau - c_n) + p_e((e_n - e_r)\tau - e_n) - A\tau)}{-2 + 4(1-\beta)\tau - 2(1-\beta)\tau^2} \quad (21)$$

$$\Pi^*_{h,C} = -\left(\frac{3e_n^2p_e^2 - 6e_np_eQ(1+\tau^2) + 3Q^2 + 3c_n^2(-1+\tau)^2 + 6e_np_e\tau(A+c_r-e_np_e) + 6e_ne_rp_e^2\tau(1-\tau) - 6(A+c_r)Q\tau(1-\tau)}{16(-1-2(-1+\beta)\tau + (-1+\beta)\tau^2)} \right.$$
$$+\frac{6p_eQ\beta\tau^2(e_n - e_r) - 3\beta\tau^2(2-\beta) + 6c_n(-1+\tau)(e_np_e(-1+\tau) - (A+c_r+e_rp_e)\tau + Q(1+(-1+\beta)\tau)) + 3p_e^2\tau^2(e_r^2 + e_n^2)}{16(-1-2(-1+\beta)\tau + (-1+\beta)\tau^2)}$$
$$+\frac{32B\tau^3(1-\beta) - 16B\tau^4(1-\beta) - 16Gp_e(-1-2(-1+\beta)\tau + (-1+\beta)\tau^2) + 6e_rp_eQ\tau(\tau-1) + 3(Q^2+A^2)\tau^2 - 6(A+c_r)Q\beta\tau^2}{16(-1-2(-1+\beta)\tau + (-1+\beta)\tau^2)}$$
$$\left.+\frac{6e_np_eQ\tau(2-\beta) - 6Q^2\tau(1-\beta) - 16B\tau^2 + 6Ac_r\tau^2 + 3c_r^2\tau^2 - 6Ap_e\tau^2(e_n - e_r) - 6c_rp_e\tau^2(e_n - e_r)}{16(-1-2(-1+\beta)\tau + (-1+\beta)\tau^2)}\right) \quad (22)$$

This proposition states that the carbon emission limits set by the government will affect the retail price of new and remanufactured products to some extent. And as the carbon emission limit increases, the retail price of the product decreases.

### C. REVENUE SHARING CONTRACT MODEL

According to the proposition 3, the centralized decision model is better than decentralized decision model, which reflects the effectiveness of centralized decision model. In order to coordinate the decentralized decision model, the revenue sharing contract is constructed to achieve the level of the centralized decision model, while ensuring that the profits of each member in the closed-loop supply chain are more than the profits under the decentralized decision model. A revenue-sharing contract means that the manufacturer sells the product to the retailer at a lower wholesale price and distributes the sales revenue to the retailer at a ratio of $(\varphi, 1-\varphi)$, where $\varphi$ is revenue shared contract parameters.

According to this contract, the profits of retailers and manufacturers can be obtained separately:

$$\Pi_{r,S} = \varphi\left(p_n q_n + p_r q_r\right) - w_n q_n - w_r q_r \tag{23}$$

$$\begin{aligned}\Pi_{m,S} = {} & (1-\varphi)\left(p_n q_n + p_r q_r\right) + \left(w_n - c_n\right) q_n + \left(w_r - c_r\right) q_r \\ & - B\tau^2 - A\tau\left(q_n + q_r\right) - p_e\left(e_n q_n + e_r q_r - G\right)\end{aligned} \tag{24}$$

where $\Pi_{r,S}$ is retailers' profit under the revenue sharing contract model; and $\Pi_{m,S}$ is the manufacturers' profit under the revenue sharing contract model.

The Hessian matrix of the retailer's profit function under the revenue sharing contract model can be obtained according to formula (23).

$$H = \begin{Bmatrix} \dfrac{2\varphi}{\beta - 1} & \dfrac{2}{1-\beta} \\ \dfrac{2}{1-\beta} & \dfrac{2\varphi}{\beta(\beta-1)} \end{Bmatrix}, \quad which \ \frac{2\varphi}{\beta - 1} < 0;$$

$$|H| = \frac{4\varphi^2}{\beta(1-\beta)} > 0$$

We can see that there is an optimal retail price that maximizes the retailer's profit. At the same time, the game is a Stackelberg game under the leadership of the manufacturer, according to the inverse induction method, take the first-order partial derivative of the $p_n$, $p_r$ in the retailer model (23), and $p_{n,S} = \frac{w_n + Q\varphi}{2\varphi}$, $p_{r,S} = \frac{w_r + Q\beta\varphi}{2\varphi}$ is obtained. The design of revenue sharing is designed to achieve the effect of centralized decision making, which means $\Pi_{h,S} = \Pi_{m,S} + \Pi_{r,S} = \Pi_{h,C}$, then we can get $p_{n,S} = p_{n,C}, p_{r,S} = p_{r,C}$. Where $\Pi_{h,S}$ is defined as the entire supply chain profit under revenue-sharing contract model.$\Pi_{h,C}$ is defined as the entire supply chain profit under the centralized decision model. $p_{n,S}, p_{r,S}$ is the retail price of new products and remanufactured products under the revenue sharing contract model, and $p_{n,C}, p_{r,C}$ is the retail price of new products and remanufactured products under the centralized decision model. Further, we can get (25) and (26), as shown at the bottom of this page, where $w_{n,S}$ is the wholesale price of new products under the revenue sharing contract model;$w_{r,S}$ is the wholesale price of remanufactured products under the revenue sharing contract model.

Substituting $w_{n,S}, w_{r,S}, p_{n,S}, p_{r,S}$ into equations (24) and (25), the profits of manufacturers and retailers under the revenue sharing contract are given in (27) and (28), as shown at the bottom of this page, where $\prod_{r,S}^*$ is the retailer's best profit under revenue-sharing contract model; $\prod_{m,S}^*$ is the manufacturer's best profit under revenue-sharing contract model.

Analyze the above results and get the following conclusions:

*Proposition 6:* If both the manufacturer and the retailer to accept the revenue-sharing contract, then the contract parameter $\varphi$ must satisfy $\frac{1}{4} \le \varphi \le \frac{1}{2}$.

This proposition states that under the shared contract coordination mechanism, the retailer can accept the contract if and only if the coordination factor $\frac{1}{4} \le \varphi \le \frac{1}{2}$. In actual operation, the specific value of $\varphi$ needs to be coordinated by both the manufacturer and the retailer according to the specific situation.

## V. NUMERICAL EXAMPLE

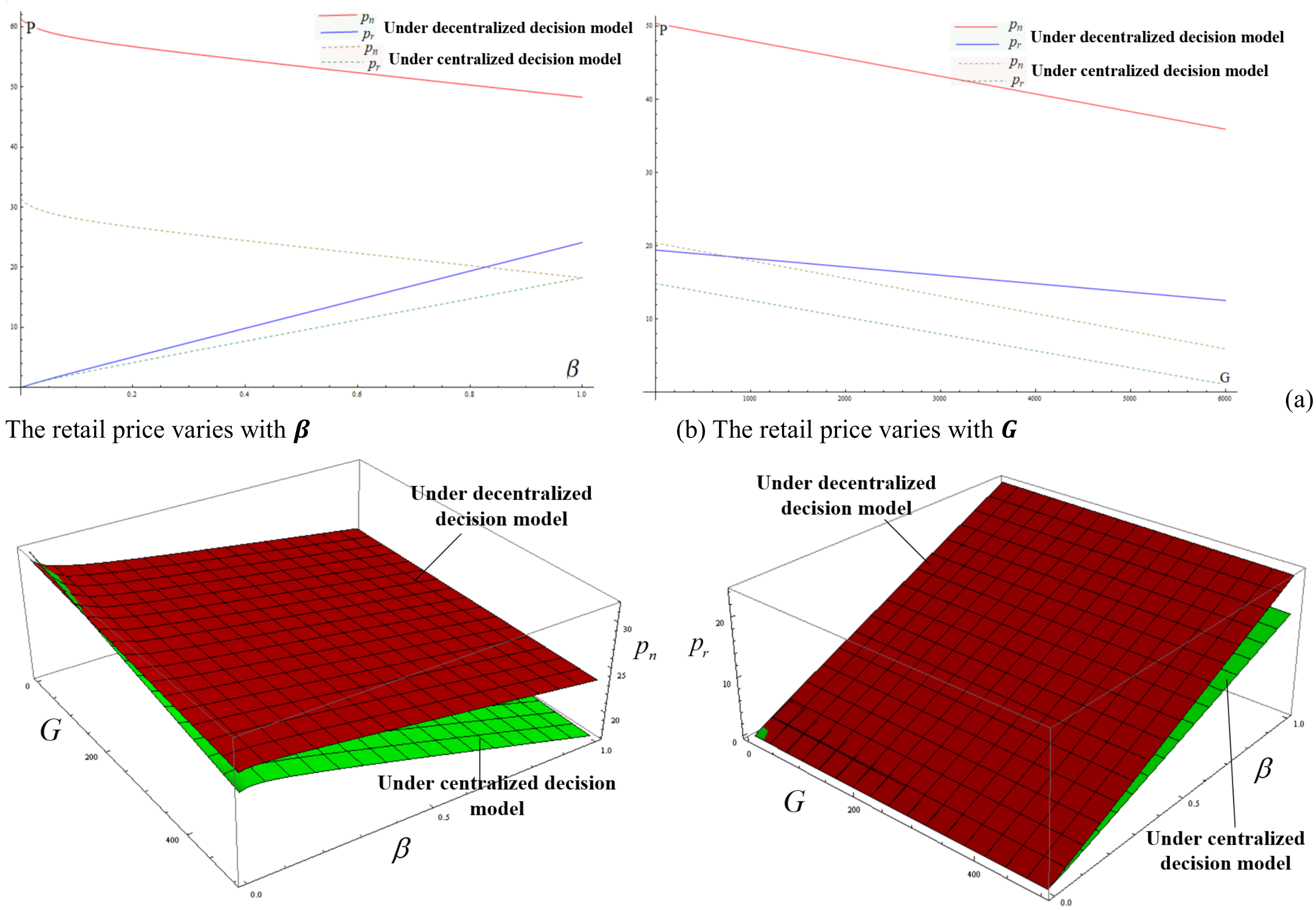
In the aforementioned models and analysis, it seems unlikely to derive analytical results thoroughly regarding the behavior of the decision and profit functions. We carried out an in-depth numerical study as a complement to exploit their property. Therefore, in this section, in order to further analyze the impact of carbon limit $G$ and WTP coefficient $\beta$ of remanufactured products on supply chain pricing and total profit, we conduct a set of numerical simulation experiments

$$w_{n,S} = \frac{\varphi\left(\left(1-(1-\beta)\tau\right)\left(c_n - (c_n - c_r)\tau + p_e\left(e_n - (e_n - e_r)\tau\right) + A\tau\right) + Q\beta\tau^2(1-\beta)\right)}{1 - 2\tau(1-\beta) + (1-\beta)\tau^2} \tag{25}$$

$$w_{r,S} = \frac{\varphi\beta\left(c_n - (c_n - c_r)\tau + p_e\left(e_n - (e_n - e_r)\tau\right)\right) + A\tau - Q\tau(1-\beta)(1-\tau)}{1 - 2\tau(1-\beta) + (1-\beta)\tau^2} \tag{26}$$

$$\Pi_{r,S}^* = \frac{\left(c_n - Q\left(1-\tau(1-\beta)\right) + A\tau - (c_n - c_r)\tau - p_e\tau\left(e_n - e_r\right) + e_n p_e\right)^2}{4\left((1-\beta)(1-\tau)^2 + \beta\right)} \tag{27}$$

$$\prod_{m,S}^* = \prod_{m,D}^* + \left(1 - \frac{1}{2\varphi}\right)\prod_{r,S}^* \tag{28}$$




The retail price varies with ***β*** (b) The retail price varies with ***G***

(c) The retail price of new products varies with ***G*** and ***β*** (d) The retail price of remanufactured products varies with ***G*** and ***β***

**FIGURE 3. The optimal retail price varies with $G$ and $\beta$.**

to verify the correctness of the proposition. We assign relevant parameters and analyzes it using the software Mathematica 8.0 as a calculation tool. Subsequently, the numerical examples describe the optimal strategies, where $Q = 30, c_n = 10, c_r = 2, e_n = 0.9, e_r = 0.5, \tau = 0.8, B = 10, a = 4, b = 0.008$ are constant values. For meaningful and reasonable schemes, the variables $G$, $\beta$, $\varphi$ are changeable.

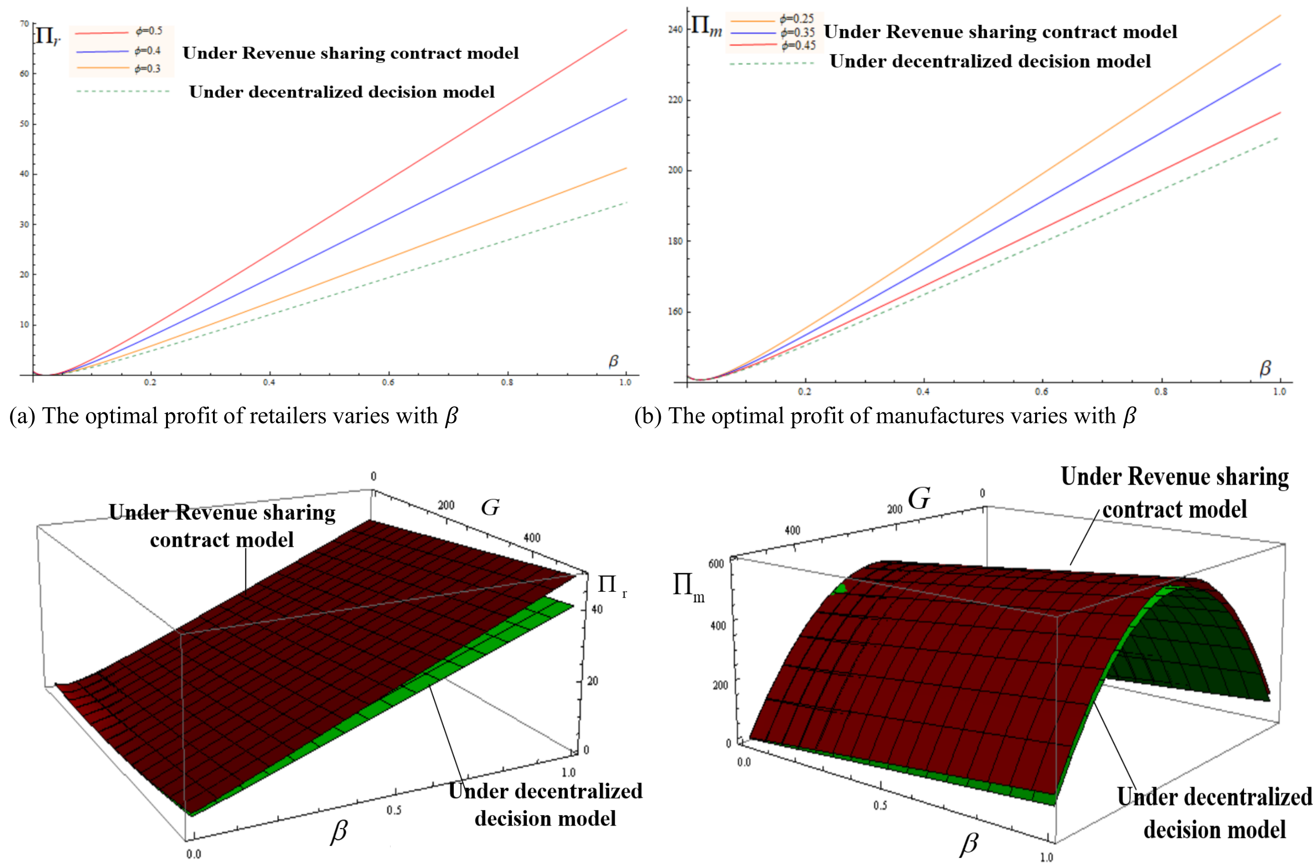
### A. COMPARISON OF THE RETAIL PRODUCTS PRICING

In this section, the retail price of the new products and remanufactured products are estimated respectively under centralized decision model and decentralized decision model, as shown in Figure 2. The impact of whole carbon emission limitation and customers' WTP on the results of retail products price are also evaluated. From the perspective of a more intuitive graphical description, we can further verify the propositions of 1, 2, 4 and 5 presented in Section IV.

(1) In Figure 2(a) and (b), the solid line indicates the retail price of new and remanufactured products under the decentralized decision model, while the dashed line indicates the retail price under the centralized model. In Fig. 2(a), we fixed the parameter $G = 40$ and $\beta$ varies between (0, 1). Then from the figure, we can see that the retail price of new products decreases as $\beta$ increases, while the retail price of remanufactured products increases as $\beta$ increases. In Fig. 2(b), we fixed the parameter $\beta = 0.8$ and $G$ varies between (0,6000). Then we can see that the retail price of new products and remanufactured products decreases as $G$ increases. Moreover, we can see from both Fig. 2(a) and (b), the retail price under the decentralized decision model is higher than the retail price under the centralized decision model.

(2) In Figure 2(c) and (d), the red mesh plane represents the retail price of new products and manufactured products under the decentralized decision model, while the green mesh plane represents the retail price under the centralized decision model. Then we set $G$ to varies between (0,500) and $\beta$ varies between (0, 1) (The above parameter range settings are to meet the feasibility of the experiment and make the experimental results clearer). From this two Fig. 2(c) and (d), we can more clearly see that the centralized decision model is better than the decentralized decision model than Fig. 2(a) and (b).

(3) In the above model simulation, the retail price of new products and remanufactured products under the two models has been clearly compared. Then we will assign different




(a) The optimal profit of retailers varies with $\beta$

(b) The optimal profit of manufactures varies with $\beta$

(c) The optimal profit of retailers varies with $G$ and $\beta$

(d) The optimal profit of manufactures varies G with $\beta$

**FIGURE 4. The profit of retailers and manufacturers varies with G and $\beta$.**

**TABLE 2. Comparison of retail prices under two models.**

| | | Centralized decision | | Decentralized decision | |
|---|---|---|---|---|---|
| | | $p_n$ | $p_r$ | $p_n$ | $p_r$ |
| G = 40 | β = 0.2 | 26.690 | 4.1613 | 56.690 | 5.0806 |
| | β = 0.4 | 24.440 | 7.7237 | 54.440 | 9.8618 |
| | β = 0.6 | 22.346 | 11.247 | 52.346 | 14.623 |
| | β = 0.8 | 20.297 | 14.759 | 50.297 | 19.379 |
| β = 0.6 | G = 100 | 22.193 | 11.111 | 52.193 | 14.555 |
| | G = 200 | 21.937 | 10.885 | 51.937 | 14.442 |
| | G = 300 | 21.681 | 10.659 | 51.681 | 14.329 |
| | G = 400 | 21.424 | 10.433 | 51.424 | 14.216 |

values to the variable $G$ and $\beta$, calculate the retail price of the new product and the remanufactured product under different conditions, and verify the rationality of the model and the proposition again with specific values, as shown in Table 2.

The numerical comparison in the table further verifies the accuracy of the model. At the same time, under decentralized decision model, the retail price of new products is inversely proportional to the value of WTP, the **Proposition 1** is demonstrated; The retail price of new products and remanufactured products is inversely proportional to the carbon emission limit, and **Proposition 2** is demonstrated. Under centralized decision model, the retail price of the new product is inversely proportional to the value of WTP, and **Proposition 4** is demonstrated; And the retail price of new products and remanufactured products is inversely proportional to the carbon emission limit, and **Proposition 5** is demonstrated.

### B. COMPARISON OF THE PROFIT

In this section, the overall profit of manufacturers, retailers and whole closed-loop supply chain are estimated respectively under decentralized decision model and Revenue sharing contract model, as shown in Figure 3 and 4. The impact of carbon emission limits and WTP on retailer profits and manufacturer profits are also evaluated. From the perspective of a more intuitive graphical description, we can further judge that the revenue sharing contract model we built is better than the decentralized decision model.

(1) In Figure 3(a) and (b), the solid line indicates the profit of the retailer and the manufacturer under the shared contract model, while the dashed line refers to the profit of the retailer and the manufacturer under the decentralized decision model. Then we fixed the parameter $G = 40$ and $\beta$ varies between (0, 1), and compare the profit of retailers and manufacturers under the decentralized decision model and

**TABLE 3.** The profit comparison of three models.

| | | Centralized decision | Decentralized decision | | | Shared contract model | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | φ = 0.25 | | | φ = 0.35 | | | φ = 0.45 | | |
| | | $\Pi_h$ | $\Pi_r$ | $\Pi_m$ | $\Pi_h$ | $\Pi_r$ | $\Pi_m$ | $\Pi_h$ | $\Pi_r$ | $\Pi_m$ | $\Pi_h$ | $\Pi_r$ | $\Pi_m$ | $\Pi_h$ |
| G = 40 | β = 0.2 | 160.40 | 4.9017 | 150.60 | 155.50 | 4.9017 | 155.50 | 160.40 | 6.8624 | 153.54 | 160.407 | 8.8231 | 151.58 | 160.40 |
| | β = 0.4 | 189.25 | 12.114 | 165.02 | 177.14 | 12.114 | 177.14 | 189.25 | 16.960 | 172.29 | 189.258 | 21.806 | 167.45 | 189.25 |
| | β = 0.6 | 218.82 | 19.506 | 179.81 | 199.31 | 19.506 | 199.31 | 218.82 | 27.308 | 191.51 | 218.826 | 35.111 | 183.71 | 218.82 |
| | β = 0.8 | 248.59 | 26.949 | 194.69 | 221.64 | 26.949 | 221.64 | 248.59 | 37.72 | 210.86 | 248.598 | 48.509 | 200.08 | 248.59 |
| β = 0.6 | G = 100 | 394.79 | 20.297 | 354.19 | 374.49 | 20.297 | 374.49 | 394.79 | 28.416 | 366.37 | 394.79 | 36.535 | 358.25 | 394.79 |
| | G = 200 | 560.20 | 21.651 | 516.90 | 538.55 | 21.651 | 538.55 | 560.20 | 30.311 | 529.89 | 560.20 | 38.972 | 521.23 | 560.20 |
| | G = 300 | 565.79 | 23.048 | 519.69 | 542.74 | 23.048 | 542.74 | 565.79 | 32.267 | 533.52 | 565.79 | 41.487 | 524.31 | 565.79 |
| | G = 400 | 411.55 | 24.489 | 362.57 | 387.06 | 24.489 | 387.06 | 411.55 | 34.285 | 377.27 | 411.55 | 44.081 | 367.47 | 411.55 |

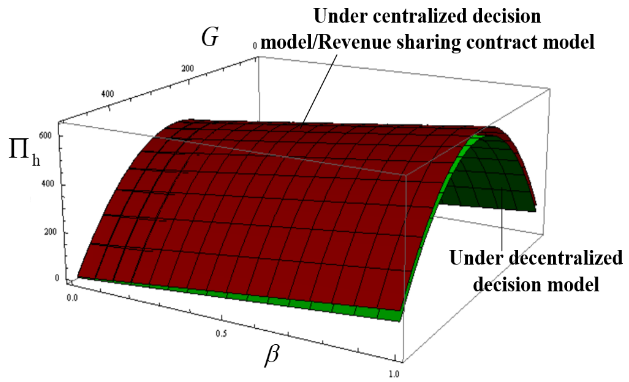



**FIGURE 5.** The profit of closed-loop supply chain system varies with G and $\beta$.

the shared contract model with $\beta$. Under the shared contract model, the impact of different contract parameters $\varphi$ on the profit of manufacturers and retailers is considered, simultaneously. Then from these two figures, we can see that the retailer's profit increases as the contract parameter $\varphi$ increases, while the manufacturing profit decreases as $\varphi$ increases. It can also be seen from the figure 3(a) and (b) that the greater the consumer's willingness to pay for remanufactured products, the greater the profits of manufacturers and retailers.

(2) In Figure 3(c) and 3(d), the red mesh plane represents the profit of the retailer and the manufacturer under the shared contract model, while the green mesh plane represents the profit of the retailer and the manufacturer under the decentralized decision model. Then we set $G$ to varies between (0,500) and $\beta$ varies between (0, 1). From Fig.3(c), we can see that the profit of retailers is increase with the carbon emission limit increase. However, the trend of manufacturers' profits with carbon emission limits is different from retailers. The profit of the manufacturer increases first and then decreases as the carbon emission limit increases, which means there exist the optimal carbon emission limit for manufacturers achieving the maximum profit. Finally, it also can be seen from figure 3 that the profit of retailers and manufacturers under the Revenue sharing contract model is better than the profit under decentralized.

(3) In Figure 4, the red mesh plane represents the profit of supply chain system under the centralized decision and shared contract model, while the green mesh plane indicates the profit of supply chain system under the decentralized decision model. From this Figure, we can see that the profit of the supply chain system under the centralized decision model is greater than the system profit under the decentralized decision model, and the shared contract model can make the profit of the decentralized decision model reach the profit under the centralized decision model. This shows that the revenue sharing contract model can achieve the maximum profit of the supply chain, and can change the profit by changing the contract parameters, which increases the flexibility of the closed-loop supply chain channel coordination.

(4) The above model simulation analysis has verified the correctness of the model. The feasibility of the model is verified again by specific numerical analysis. Numerical results are summarized in Table 2. The data in the table proves that whether it is a manufacturer or a retailer, whether it is a centralized decision model or a decentralized decision model, its profit is proportional to the value of WTP. However, the profit of the supply chain system first increases with the increase of the carbon limit and then decreases with the increase of the carbon limit. There has the optimal carbon limit makes the system profit reach the optimal state. For example, in Fig.4 we can see that the system profit of the supply chain reaches the maximum when $G = 300$ or so.

## VI. CONCLUSION

This paper proposed a Revenue-sharing contract model to coordinate decentralized decision model, then to maximize the overall profit of the closed-loop supply chain considering the carbon cap and trade and consumers' different willingness to pay for remanufactured products. We assume that the government stipulates that the company's carbon emission limits and the willingness to pay will affect the pricing of products and the profit of the supply chain. We have shown that the process of establishing the optimal pricing model and the related propositions and results. Finally, we analyzed the impact of carbon emission limits and WTP on product pricing and profitability of manufacturers and retailers and the entire closed-loop supply chain through numerical simulation.

According to the study of this paper, we have three results. First, consumers' WTP for remanufactured products will affect the price of remanufactured products, which will affect the profits of retailers and manufacturers. The results of the study show that the greater the willingness to pay, the higher the retail price of remanufactured products, and the higher the profits of manufacturers and retailers. Second, the carbon emission limit will also affect the price of new and remanufactured products and the profit of closed-loop supply chain. As carbon emission limits increase, the retail prices of new and remanufactured products will decline. However, the function image of the closed-loop supply chain profit and carbon limit is an inverted U shape which means the government can set a suitable carbon emission limit, which maximizes the profit of the closed-loop supply chain and can reasonably control the pollution caused by carbon emissions. Third, from the numerical study, we can see, the centralized decision model is more efficient than the decentralized decision model. The profit of manufacturers, retailers, and closed-loop supply chain systems under decentralized decision model is not optimal, there is further optimization space.

In this study, we only consider the effects of carbon emission limit and WTP on the pricing strategy and profit of closed-loop supply chain. However, the recycling of waste materials is a very complicated process. The recovery rate of these discarded products is significantly related with many factors, e.g. the government's subsidy policy and different sales channels, which have great uncertainty affecting the pricing strategy and profit of closed-loop supply chain. Therefore, the effects of recovery rate on product pricing and profit of closed-loop supply chain should be further expanded on this basis.

## APPENDIX

*Proof of Assumption:* To prove the equation of $p_n = Q - q_n - \beta q_r$ and $p_r = \beta (Q - q_r - q_n)$ are reasonable, we assume the price K that consumers are a willingness to pay for new products is subject to a uniform distribution of [0, $Q$], and the price that consumers are willing to pay for remanufactured products is $\beta$K [14]. The net utility of purchasing new and remanufactured products is the price that the consumers are a willingness to pay minus the retail price, which are $u_n$ and $u_r$ respectively.

$$u_n = \mathrm{K} - p_n \tag{a}$$

$$u_r = \beta\mathrm{K} - p_r \tag{b}$$

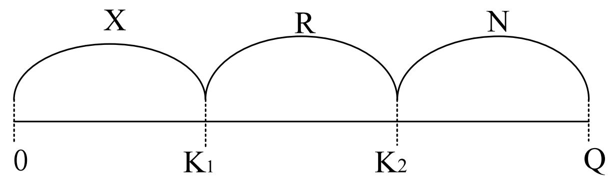



**FIGURE 6. Consumer purchase selection decision diagram.**

Consumers face three options: buying new products (N), buying remanufactured products (R), and not buying enough products (X). Figure 1 shows the decision-making options for consumers who are willing to buy a product and not to buy any product.

When consumers purchase remanufactured products, the minimum value of $K$ is $K_1 = Q - q_n - q_r$, at this time, it is at the critical point of purchasing remanufactured products and not purchasing any products, so the consumer's utility is equal. According to formula (a), the net utility of purchasing remanufactured products is $u_r = \beta \mathrm{K}_1 - p_r = \beta (Q - q_n - q_r) - p_r$, while the net utility of not buying any product is 0, we can get $p_r = \beta (Q - q_r - q_n)$. Similarly, we can get $p_n = Q - q_n - \beta q_r$.

*Proof of Proposition 1:* To prove the wholesale price and retail price of new products are inversely proportional to the value of WTP and to prove the wholesale and retail prices of re-manufactured products are directly proportional to the value of WTP under the decentralized decision model. We take the first-order partial derivative for $\beta$ of the equation $w^*_{n,D}$, $w^*_{r,D}$, $p^*_{n,D}$,$p^*_{r,D}$, we can get (29a)–(29d), as shown at the top of the next page.

From the assumption we can know:

$$0 < \tau, \quad \beta < 1, c_n > c_r, \; e_n > e_r$$

Therefore, $\tau(1 - \tau)((-c_n + (c_n - c_r)\,\tau) < 0$

$$p_e((e_n - e_r)\tau - e_n) - A\tau) < 0$$

$$Q\tau^2((1 - 2\beta) - \tau \left(1 - \beta\right)^2 (2 - \tau)\right) < 0$$

Further, $\frac{\partial w^*_n}{\partial \beta} < 0$

Similarly, $\frac{\partial p^*_n}{\partial \beta} < 0$, $\frac{\partial w^*_r}{\partial \beta} > 0$, $\frac{\partial p^*_r}{\partial \beta} > 0$

The proposition is proved.

*Proof of Proposition 2:* To prove the wholesale and retail prices of new and remanufactured products are inversely proportional to the carbon emission limit under decentralized decision model, considering the first-order partial derivative for $G$ of the equation $w^*_n$, $w^*_r$,$p^*_n$, $p^*_r$, we can get:

$$\frac{\partial w^*_n}{\partial G} = \frac{b(-e_n + (e_n - e_r)\tau)(-1 + (1 - \beta)\tau)}{-2 + 4(1 - \beta)\tau - 2(1 - \beta)\tau^2} \tag{30a}$$

$$\frac{\partial p^*_n}{\partial G} = \frac{b(-e_n + (e_n - e_r)\tau)(-1 + (1 - \beta)\tau)}{-4 + 8(1 - \beta)\tau - 4(1 - \beta)\tau^2} \tag{30b}$$

$$\frac{\partial w^*_r}{\partial G} = \frac{b\beta(e_n - (e_n - e_r)\tau)}{-2 + 4(1 - \beta)\tau - 2(1 - \beta)\tau^2} \tag{30c}$$

$$\frac{\partial p^*_r}{\partial G} = \frac{b\beta(e_n - (e_n - e_r)\tau)}{-4 + 8(1 - \beta)\tau - 4(1 - \beta)\tau^2} \tag{30d}$$

$$\frac{\partial w_n^*}{\partial \beta} = \frac{\tau(1-\tau)((-c_n+(c_n-c_r)\tau)+p_e((e_n-e_r)\tau - e_n) - A\tau) + Q\tau^2((1-2\beta) - \tau(1-\beta)^2(2-\tau))}{2(1-2(1-\beta)\tau + (1-\beta)\tau^2)^2} \tag{29a}$$

$$\frac{\partial p_n^*}{\partial \beta} = \frac{\tau(1-\tau)((-c_n+(c_n-c_r)\tau) - p_e((e_n-e_r)\tau - e_n) - A\tau) + Q\tau(2(1-\beta\tau) - (\tau^2(1-\beta)^2+1)(2-\tau))}{4(1-2(1-\beta)\tau + (1-\beta)\tau^2)^2} \tag{29b}$$

$$\frac{\partial w_r^*}{\partial \beta} = \frac{(1-\tau)^2(c_n-(c_n-c_r)\,\tau)+p_e\,(e_n-(e_n-e_r)\,\tau)+A\tau)+Q(1+(-5+6\beta)\tau+(9-16\beta+6\beta^2)\tau^2-\tau^3(1-\beta)^2(7-2\tau))}{2(1-2(1-\beta)\tau+(1-\beta)\tau^2)^2} \tag{29c}$$

$$\frac{\partial p_r^*}{\partial \beta} = \frac{(1-\tau)^2\,(c_n-(c_n-c_r)\,\tau+p_e\,((e_n-e_r)\,\tau-e_n)-A\tau)+Q(3-13\tau+14\beta\tau+\tau^2(21-36\beta+14\beta)^2+(1-\beta)^2\tau^3(-15+4\tau))}{4(1-2(1-\beta)\tau + (1-\beta)\tau^2)^2} \tag{29d}$$

$$\frac{\partial p_{n,C}^*}{\partial \beta} = \frac{\tau(1-\tau)((-c_n+(c_n-c_r)\tau)+p_e(-e_n+(e_n-e_r)\tau) - A\tau) + Q\tau^2((1-2\beta) - \tau(1-\beta)^2(2-\tau))}{2(1-2(1-\beta)\tau + (1-\beta)\tau^2)^2} < 0 \tag{32a}$$

$$\frac{\partial p_{r,C}^*}{\partial \beta} = \frac{(1-\tau)^2(c_n-(c_n-c_r)\tau+p_e(e_n-(e_n-e_r)\tau)+A\tau)}{2(1-2(1-\beta)\tau+(1-\beta)\tau^2)^2} + \frac{Q(1-(5-6\beta)\tau+\tau^2(9-16\beta+6\beta^2)+(1-\beta)^2\tau^3(2\tau-7))}{2(1-2(1-\beta)\tau+(1-\beta)\tau^2)^2} < 0 \tag{32b}$$

According to assumptions we can be obtained:

$$\begin{aligned} &-2+4\,(1-\beta)\,\tau-2\,(1-\beta)\,\tau^2 \\ &= 2\left(-1+2\,(1-\beta)\,\tau-(1-\beta)\,\tau^2\right) < 2(-1+\beta \\ &\quad +2(1-\beta)\tau-(1-\beta)\tau^2) = -2(1-\beta)(1-\tau)^2 < 0 \\ &\quad b(-e_n+(e_n-e_r)\tau)(-1+(1-\beta)\tau) > 0 \end{aligned}$$

Therefore, $\frac{\partial w_n^*}{\partial G} < 0$

Similarly, $\frac{\partial p_n^*}{\partial G} < 0$, $\frac{\partial w_r^*}{\partial G} < 0$, $\frac{\partial p_r^*}{\partial G} < 0$

The proposition is proved.

*Proof of Proposition 3:* To prove the profit of the supply chain under a centralized decision model is better than the profit under decentralized decision model. We let T $=\Pi_{h,C}^* - \Pi_{h,D}^*$ and we get:

$$\begin{aligned} &\mathrm{T} \\ &= \frac{(c_n+(A-c_n+c_r)\tau+p_e(e_r\tau+e_n(1-\tau))+Q(-1+\tau-\beta\tau))^2}{16\left(1+2(-1+\beta)\,\tau+(1-\beta)\,\tau^2\right)} \\ &\quad \times 16\left(1+2\,(-1+\beta)\,\tau+(1-\beta)\,\tau^2\right) > 0 \end{aligned} \tag{31a}$$

Therefore, T $=\Pi_{h,C}^* - \Pi_{h,D}^* > 0$, $\Pi_{h,C}^* > \Pi_{h,D}^*$

The proposition is proved.

*Proof of Proposition 4:* To prove the retail price of a new product is inversely proportional to the value of WTP, and the retail price of a re-manufactured product is proportional to the value of WTP. We take the first-order partial derivative for $\beta$ of the equation $p_{n,C}^*$, $p_{r,C}^*$, we can get (32a) and (32b), as shown at the top of this page.

The proposition is proved.

*Proof of Proposition 5:* To prove the retail price of new products and the retail price of re-manufactured products are inversely proportional to the carbon emission limit under centralized decision model. We take the first-order partial derivative for $G$ of the equation $p_{n,C}^*$, $p_{r,C}^*$, we can get:

$$\frac{\partial p_{n,C}^*}{\partial G} = \frac{b(e_n-(e_n-e_r)\tau)(1-(1-\beta)\tau)}{-2+4(1-\beta)\tau-2(1-\beta)\tau^2} \tag{33a}$$

$$\frac{\partial p_{r,C}^*}{\partial G} = \frac{b\beta(e_n-(e_n-e_r)\tau)}{-2+4(1-\beta)\tau-2(1-\beta)\tau^2} \tag{33b}$$

According to assumptions we can be obtained:

$$\begin{aligned} &-2+4(1-\beta)\tau-2(1-\beta)\tau^2 \\ &= 2(-1+2(1-\beta)\tau-(1-\beta)\tau^2) < 2(-1+\beta+2(1-\beta)\tau \\ &\quad -(1-\beta)\tau^2) = -2(1-\beta)(1-\tau)^2 < 0 \\ &\quad \times b(e_n-(e_n-e_r)\tau)(1-(1-\beta)\tau) > 0 \end{aligned}$$

Therefore, $\frac{\partial p_{n,C}^*}{\partial G} < 0$

Similarly, $\frac{\partial p_{r,C}^*}{\partial G} < 0$

The proposition is proved.

*Proof of Proposition 6:* In order for the retailer and the manufacturer to accept the revenue sharing contract, we must satisfy $\prod_{r,S}^* \geq \prod_{r,C}^*, \prod_{m,S}^* \geq \prod_{m,C}^*, \prod_{r,S}^* - \prod_{r,C}^* = \frac{1}{4} \geq 0$, gets $\varphi \geq \frac{1}{4}$, and the same can be obtained when the manufacturer's profit under the revenue sharing contract is greater than the manufacturer's profit under the decentralized decision, satisfying $\varphi \leq \frac{1}{2}$, the certificate is completed.

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