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A Coordinated Revenue-Sharing Model for a Sustainable Closed-Loop Supply Chain

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Abstract: This study takes a sustainable closed-loop supply chain composed of one manufacturer and two price-competitive retailers as the object and considers the two-way risk aversion characteristics of manufacturers and retailers in examining the coordination mechanism in a closed-loop supply chain. Using game theory, optimal decision-making on wholesale prices, retail prices, and recycling prices are explored under decentralized and centralized decision-making scenarios, and representative expressions are established. By analyzing the effects of the risk aversion coefficient on players' optimal strategies, we found that the manufacturer's and retailers' risk aversion coefficients have different effects on the wholesale price, retail price, and recycling price under decentralized decision-making, while in a centralized decision-making scenario, the effects are the same. The comparison also found that the wholesale price and recovery price under the centralized decision-making scenario are higher than those under decentralized decision-making. To achieve closed-loop supply chain coordination, we propose a revenue-sharing contract that we demonstrate by coordinating price competition with risk aversion and analyze a range of parameters that influence the revenue-sharing contract. The results show that the proposed contract can increase the profits of supply chain members by identifying the optimal revenue-sharing ratio.

Keywords: sustainable closed-loop supply chain; revenue-sharing contract; risk aversion; price competition; simulation analysis; model

1. Introduction

In recent years, an increasing focus on environmental protection and sustainable development have led many industries to pursue green management. A sustainable closed-loop supply chain (SCLSC) recycles waste products, which not only reduces manufacturing costs and increases profit margins, but also reduces carbon emissions and environmental pollution, and thus plays a significant role in environmental protection [1]. A CLSC not only enhances the competitiveness of the company but also enables the sustainable development of the company [2]. In practice, world-renowned companies such as Canon, Xerox, and Dell are typical of CLSC [3]. At the same time, the data show that recycled products account for about 8.89% or 286 billion US dollars of sales in the United States [4]. According to the statistics of the Ministry of Industry and Information Technology, at the end of January 2014, China Mobile Communications reached 1.235 billion, an increase of 0.5% from the previous month and an increase of 10.8% over the previous year which has surpassed the United States to become the world's number one. Obviously, China's current recycling of used mobile phones needs to be urgently resolved. It needs to be systematically planned and systematically guided for long-term development and planning.

When product functions are similar, customers compare similar or alternative products offered by different retailers, and price is an important factor in their purchase decision. At the same time, retailers are responsible for recycling used products in the market, and this recycling process also has the characteristics of price-based competition [5]. In the face of uncertain markets, supply chain members often display risk preference characteristics in relation to product sales and waste recycling, and their attitude to risk plays an important role in decision-making. In general, the utility of supply chain members is an increasing function of expected profits, but both are declining with risk-sensitive functions [6]. Today, the question of how to balance expected profits and risk aversion is particularly important. When supply chain members display risk-averse characteristics, how the risk aversion coefficients affect each other, how the decision-making of upstream and downstream nodes can be influenced, and how the interests of the supply chain system can be met require further exploration.

This study considers the characteristics of risk aversion and price competition and constructs a CLSC contract coordination model. The remainder of this paper is organized as follows: Section 2 presents a comprehensive review of the literature on risk aversion and price competition, focusing on CLSC. The notation and assumptions used in this paper are described in Section 3. Section 4 addresses the development and analysis of different models. Section 5 presents a numerical analysis, including sensitivity analysis of the relevant parameters. Section 6 concludes and outlines future research directions.

2. Literature Review

The role of CLSC as an important part of sustainable operations management has always been a hot topic in green supply chain management research [7]. In recent years, numerous scholars have conducted in-depth studies of CLSC structure designs [8–10], coordination mechanisms [11–13], and recycling channels [14–16]. In relation to the competitive environment, competition between different levels of the supply chain is called vertical competition, and competition at the same level of the supply chain is called horizontal competition. The study of vertical competition in relation to CLSC mainly involves the network equilibrium model [17–19], while horizontal competition includes competition between single-tier retailers or single-layer manufacturers, and between retailers and manufacturers. Wei and Zhao [20] studied the problem of price competition among retailers by considering the fuzzy characteristics of demand and costs. Jena and Sarmah [5] considered a CLSC consisting of two manufacturers and a single retailer, and analyzed the pricing problem under wholesale price competition among manufacturers. Wang et al. [21] studied the reward and punishment mechanisms of CLSC under conditions of price competition among manufacturers. Xie et al. [11] studied the contract coordination mechanism under the condition of channel sales price competition based on a dual-channel CLSC. Wang et al. [22] studied the decision-making problem in various modes based on the price competition characteristics of the sales market and the recycling market.

The abovementioned studies on CLSCs are based on risk-neutral situations. However, in real life, the decision-making process often includes risk preference characteristics. Existing metrics for supply chain risk aversion include value at risk (VaR) [23–25], mean–variance (MV) [26,27], and conditional value at risk (CVaR) [28–30]. Xiao and Yang [31] studied the impact of the retail price risk avoidance coefficient on optimal decision-making by considering sales price and service competition characteristics. Liu et al. [32] considered dual-channel price competition characteristics and studied the decision-making problem in a risk-averse supply chain under information asymmetry. Li et al. [29] considered the risk aversion characteristics of retailers and studied the contract coordination problem in supply chains under channel price competition. Although these studies of the risk aversion characteristics of supply chains consider various risk measurement methods, types of price competition, and channel structures, they have rarely considered a CLSC.

In summary, the existing literature does not comprehensively examine CLSC in relation to price competition and risk aversion characteristics. Based on the existing research, this study presents a comprehensive analysis of these factors, focusing on the impact of the risk aversion coefficient on various prices.

3. Notations and Assumptions

This study considers a CLSC consisting of one manufacturer and two price-competitive retailers, all of whom exhibit risk-averse characteristics. Based on the traditional CLSC coordination theory, a corresponding revenue-sharing contract coordination model is constructed.

The notations used throughout the paper are as follows:

$U(\pi_{ri})$	utility function of the retailer
$U(\pi)$	utility function of the overall system
$()^d$	decentralized policy
$()^c$	centralized policy
$()^o$	revenue sharing
s	income distribution coefficient, where $0 < s < 1$
η_r	retailer's risk aversion factor
η_m	manufacturer's risk aversion factor
i	specific retailer, where $i = 1, 2$
D_i	demand at the retailer's store
Q_i	quantity of recycled products at the retailer's store
c_i	unit cost of retail sales, where $c_i = c_r$
c_{ri}	unit cost of recycling by the retailer, where $c_{ri} = c_{rz}$
w_m	unit wholesale price from the manufacturer
c_m	unit production cost of the manufacturer
c_{mz}	unit remanufacturing cost of the manufacturer
p_i	unit retail sale price, where $p_i > w_m + c_r > c_m + c_r$
p_{ri}	unit retail recycling price
p_m	unit recycling price of the manufacturer, where $p_{ri} + c_{ri} < p_m < c_m - c_{mz}$
$U(\pi_m)$	utility function of the manufacturer
a	total sales market volume, which displays a normal distribution with mean $\overline{a}$ and variance δ_a
β	demand sensitivity of a retailer to its own service level
γ	demand sensitivity of a retailer to the rival's service level, where $\beta > \gamma > 0$
b	total recycling market capacity, which displays a normal distribution with mean $\overline{b}$ and variance δ_b
h	recycling sensitivity of a retailer to its own service level
λ	recycling sensitivity of a retailer to the rival's service level, where $h > \lambda > 0$.

The following assumptions are made to develop the proposed model:

(1) As rational economic people, the manufacturer and two retailers each make decisions based on the principle of maximizing profit, while they are all risk-averse.

(2) The retail process of the two retailers is non-independent and represents Cournot competition. Similar to Yao et al. [33], we assume that the demand function of retailer i is given by $D_i = a - \beta p_i + \gamma p_{3-i}$ $(i = 1, 2)$.

(3) The recycling process for the two retailers' waste products is non-independent and represents Cournot competition. Similar to Yao et al. [33], we assume that the quantity of recycled products of retailer i is given by $Q_i = b + hp_{ri} - \lambda p_{r(3-i)}$ $(i = 1, 2)$.

(4) Considering risk sensitivity, we assume that each retailer and the manufacturer assess their utility using the following mean–variance value function of random profits [34]:

$$U(\pi_m) = E(\pi_m) - \eta_m Var(\pi_m),\ U(\pi_{ri}) = E(\pi_{ri}) - \eta_{ri} Var(\pi_{ri}).$$

4. Model and Analysis

In the CLSC constructed in this study, the manufacturer is responsible for the production and remanufacturing of the product, while the two retailers are responsible for the sales and recycling of the product. The relationship between the manufacturer and the retailers obeys that in the master–slave game, in which the manufacturer is in a leading position. First, the manufacturer determines the wholesale prices of the new product and the recycling price of the used product based on its own production and recycling costs. Then, the retailers determine the selling prices of the new product and the recycling price of the used product based on the manufacturer's pricing.

With the development of the Internet, online sales and online recycling have emerged, and compared with the traditional way, it has certain advantages. Huawei's mobile phone, which is the most popular domestic mobile phone in China, is a high-quality product and has a good reputation. Affected by the preference of online and offline consumption methods, Huawei's mobile phone sales and recycling process are competitive. The process which manufacturer sends the new mobile phone to the retailer through the distribution center, and then the retailer sells the new mobile phone to the consumer through online and offline methods is a positive sales channel for Huawei mobile phones. At the same time, the process by which retailers recycle old mobile phones online and offline, and send them to manufacturers for remanufacturing is Huawei's mobile phone reverse recycling channel. Due to the confidentiality of business information and the diversity of independent choices, node enterprises related to Huawei's mobile phones generally do not share information, and their decisions are decentralized. However, if centralized decision-making is achieved through information sharing, the revenue of each node enterprise will be optimal. Similar to previous studies [35], this process is analyzed in terms of the decentralized decision-making process, the centralized decision-making process, and the contract coordination process.

4.1. Decentralized Decision-Making Model

In the decentralized decision-making process, manufacturers and retailers are independent self-interested parties. As rational economic people, they aim to maximize their profits. The manufacturer acts as the Stackelberg leader, while the retailers act as followers. The manufacturer first determines the optimal unit product wholesale price w_m and the waste product unit recycling price p_m, and then the two retailers determine their own product sales price p_i and waste recycling price p_{ri}. The game is researched in the opposite way, where the retailer provides the best response to the manufacturer, and then the manufacturer decides the best decision. At this point, the utility functions of the manufacturer and retailer can be expressed as:

$$U(\pi_m^d) = \sum_{i=1}^{2}\left\{(w_m - c_m)\overline{D}_i + (c_m - c_{mz} - p_m)\overline{Q}_i - \eta_m[(w_m - c_m)^2\delta_a^2 + (c_m - c_{mz} - p_m)^2\delta_b^2]\right\} \quad (1)$$

$$U(\pi_{ri}^d) = (p_i - w_m - c_i)\overline{D}_i + (p_m - p_{ri} - c_{ri})\overline{Q}_i - \eta_r[(p_i - w_m - c_i)^2\delta_a^2 + (p_m - p_{ri} - c_{ri})^2\delta_b^2] \quad (2)$$

From the reverse derivation rule, the retailer first determines the optimal product selling price p_i and the recycling price p_{ri}, and then the manufacturer determines the optimal product wholesale price w_m and the recycling price p_m. In accordance with the necessary conditions of the first-order optimal, p_i and p_{ri} are given by:

$$\partial U(\pi_{ri}^d)/\partial p_i = \overline{a} + (\beta + 2\eta_r\delta_a^2)(w_m + c_r) - (2\beta - \gamma + 2\eta_r\delta_a^2)p_i \quad (3)$$

$$\partial U(\pi_{ri}^d)/\partial p_{ri} = (p_m - c_{ri})(h + 2\eta_r\delta_b^2) - \overline{b} - (2h - \lambda + 2\eta_r\delta_b^2)p_{ri} \quad (4)$$

Since $\partial^2 U(\pi_{ri}^d)/\partial {p_i}^2 = -(2\beta - \gamma + 2\eta_r\delta_a^2) < 0$ and $\partial^2 U(\pi_{ri}^d)/\partial {p_{ri}}^2 = -(2h - \lambda + 2\eta_r\delta_b^2) < 0$, let $\partial U(\pi_{ri}^d)/\partial p_i = 0$, $\partial U(\pi_{ri}^d)/\partial p_{ri} = 0$. Therefore, the optimal sales price p_i^d and the recycling price p_{ri}^d

determined by the retailer at the time of decentralized uncoordinated decision-making can be obtained as follows:

$$p_i^d = [\bar{a} + (\beta + 2\eta_r\delta_a^2)(w_m + c_r)]/(2\beta - \gamma + 2\eta_r\delta_a^2)(i = 1,2) \tag{5}$$

$$p_{ri}^d = [(p_m - c_{ri})(h + 2\eta_r\delta_b^2) - \bar{b}]/(2h - \lambda + 2\eta_r\delta_b^2)(i = 1,2). \tag{6}$$

Substituting p_i^d and p_{ri}^d into the manufacturer's utility function, let $\partial U(\pi_m^d)/\partial w_m = 0$ and $\partial U(\pi_m^d)/\partial p_m = 0$. Therefore, the optimal product wholesale price w_m^d and recycling price p_m^d determined by the manufacturer when decentralized uncoordinated decision-making is applied are given by:

$$w_m^d = \frac{(\beta + 2\eta_r\delta_a^2)[\bar{a} - (c_m + c_r)(\beta - \gamma)]}{2(\beta - \gamma)(\beta + 2\eta_r\delta_a^2) + 2\eta_m\delta_a^2(2\beta - \gamma + 2\eta_r\delta_a^2)} + c_m \tag{7}$$

$$p_m^d = \frac{(h + 2\eta_r\delta_b^2)[(c_{mz} + c_{rz} - c_m)(h - \lambda) - \bar{b}]}{2(h - \lambda)(h + 2\eta_r\delta_b^2) + 2\eta_m\delta_b^2(2h - \lambda + 2\eta_r\delta_b^2)} + (c_m - c_{mz}) \tag{8}$$

Proposition 1. *Under decentralized decision-making, the manufacturer's optimal wholesale price w_m^d is negatively correlated with its own risk aversion coefficient η_m and positively correlated with the retailer's risk aversion coefficient η_r, while the recycling price p_m^d is positively correlated with its own risk aversion coefficient η_m and negatively correlated with the retailer's risk aversion coefficient η_r.*

Proof. w_m^d and p_m^d are derived from the risk aversion coefficients η_m and η_r, respectively:

$$\frac{\partial w_m^d}{\partial \eta_m} = \frac{-2\delta_a^2(2\beta - \gamma + 2\eta_r\delta_a^2)(\beta + 2\eta_r\delta_a^2)[\bar{a} - (c_m + c_r)(\beta - \gamma)]}{[2(\beta - \gamma)(\beta + 2\eta_r\delta_a^2) + 2\eta_m\delta_a^2(2\beta - \gamma + 2\eta_r\delta_a^2)]^2} \tag{9}$$

$$\frac{\partial w_m^d}{\partial \eta_r} = \frac{[\bar{a} - (c_m + c_r)(\beta - \gamma)][4\eta_m\delta_a^4(\beta - \gamma)]}{[2(\beta - \gamma)(\beta + 2\eta_r\delta_a^2) + 2\eta_m\delta_a^2(2\beta - \gamma + 2\eta_r\delta_a^2)]^2} \tag{10}$$

$$\frac{\partial p_m^d}{\partial \eta_m} = \frac{2\delta_b^2(2h - \lambda + 2\eta_r\delta_b^2)(h + 2\eta_r\delta_b^2)[\bar{b} + (c_m - c_{mz} - c_{rz})(h - \lambda)]}{[2(h - \lambda)(h + 2\eta_r\delta_b^2) + 2\eta_m\delta_b^2(2h - \lambda + 2\eta_r\delta_b^2)]^2} \tag{11}$$

$$\frac{\partial p_m^d}{\partial \eta_r} = \frac{-[\bar{b} + (c_m - c_{mz} - c_{rz})(h - \lambda)][4\eta_m\delta_b^4(h - \lambda)]}{[2(h - \lambda)(h + 2\eta_r\delta_b^2) + 2\eta_m\delta_b^2(2h - \lambda + 2\eta_r\delta_b^2)]^2} \tag{12}$$

Since $p_i > w_m + c_r > c_m + c_r$ and $D_i = a - \beta p_i + \gamma p_{3-i} > 0$, we obtain:

$$\partial w_m^d/\partial \eta_m < 0,\ \partial w_m^d/\partial \eta_r > 0, \text{ and } c_m - c_{mz} > p_m, \text{ and } p_m > p_{ri} + c_{ri}$$

$Q_i = b + hp_{ri} - \lambda p_{r(3-i)} > 0$, thus, we obtain:

$$\partial {p_m}^d/\partial \eta_m > 0,\ \partial p_m^d/\partial \eta_r < 0$$

Proposition 1 shows that the manufacturer's pricing decision is affected not only by its own risk aversion coefficient but also by the retailer's risk aversion coefficient. Specifically, the wholesale price decreases as the manufacturer's risk increases, while it increases as the retailer's risk increases. Meanwhile, the recycling price increases as the manufacturer's risk increases while it decreases as the retailer's risk increases.

Proposition 2. *Under decentralized decision-making, the optimal sales price p_i^d determined by the retailer is negatively correlated with its risk aversion coefficient η_r and the manufacturer's risk aversion coefficient η_m,* *while the waste product recycling price p_{ri}^d is positively correlated with its own risk aversion coefficient η_r and the manufacturer's risk aversion coefficient η_m.*

Proof. p_i^d and p_{ri}^d are derived from the risk aversion coefficient η_r as follows:

$$\partial p_i^d/\partial\eta_r = [-2\delta_a^2[\overline{a} - (\beta - \gamma)(w_m + c_r)]]/(2\beta - \gamma + 2\eta_r\delta_a^2)^2$$

$$\partial p_{ri}^d/\partial\eta_r = [2\delta_b^2[\overline{b} + (p_m - c_{ri})(h - \lambda)]]/(2h - \lambda + 2\eta_r\delta_b^2)^2$$

Since $p_i > w_m + c_r$ and $D_i = a - \beta p_i + \gamma p_{3-i} > 0$, we obtain:

$$\partial p_i^d/\partial\eta_r < 0 \text{ and } p_m > p_{ri} + c_{ri}$$

$Q_i = b + hp_{ri} - \lambda p_{r(3-i)} > 0$, thus, we obtain:

$$\partial p_{ri}^d/\partial\eta_r > 0$$

Substituting w_m^d and p_m^d into Equations (5) and (6), p_i^d and p_{ri}^d, respectively, delineate the risk aversion coefficient η_m:

$$\partial p_i^d/\partial\eta_m = (\beta + 2\eta_r\delta_a^2)/(2\beta - \gamma + 2\eta_r\delta_a^2) * \partial w_m^d/\partial\eta_m$$

$$\partial p_{ri}^d/\partial\eta_r = (h + 2\eta_r\delta_b^2)/(2h - \lambda + 2\eta_r\delta_b^2) * \partial {p_m}^d/\partial\eta_m$$

Since $\partial w_m^d/\partial\eta_m < 0$ and $\partial {p_m}^d/\partial\eta_m > 0$, we obtain:

$$\partial p_i^d/\partial\eta_m < 0,\ \partial p_{ri}^d/\partial\eta_m < 0$$

Proposition 2 shows that the retailer's pricing decision is affected not only by its own risk aversion coefficient but also by that of the manufacturer. Specifically, the sales price decreases with an increase in both its own and the manufacturer's risk aversion coefficient, while the recycling price of waste products increases with an increase in both its own and the manufacturer's risk aversion coefficient.

Corollary 1. *Under decentralized decision-making, when both manufacturers and retailers are fully risk-averse ($\eta_m \to \infty$, $\eta_r \to \infty$), we obtain:*

$$w_m^d = c_m,\ p_m^d = c_m - c_{mz},\ p_i^d = w_m^d + c_r = c_m + c_r,\ p_{ri}^d = p_m^d - c_{rz} = c_m - c_{mz} - c_{rz}$$

Proof. Substituting $\eta_m \to \infty$ and $\eta_r \to \infty$ into the formula, Equations (5)–(8) can be obtained.

Corollary 1 indicates that when the manufacturer and retailer do not allow for any risk, their utility function is zero.

Substituting w_m^d and p_m^d into Equations (5) and (6) enables us to obtain the optimal selling price p_i^d and the recycling price p_{ri}^d determined by the retailer. Furthermore, under decentralized decision-making, the utility function values of the manufacturer, the retailers, and the supply chain as a whole can be expressed as:

$$U(\pi_m^d) = \sum_{i=1}^{2}\left\{(w_m^d - c_m)\overline{D}_i + (c_m - c_{mz} - p_m^d)\overline{Q}_i - \eta_m[(w_m^d - c_m)^2\delta_a^2 + (c_m - c_{mz} - p_m^d)^2\delta_b^2]\right\} \quad (13)$$

$$U(\pi_{ri}^d) = (p_i^d - w_m^d - c_i)\overline{D}_i + (p_m^d - p_{ri}^d - c_{ri})\overline{Q}_i - \eta_r[(p_i^d - w_m^d - c_i)^2\delta_a^2 + (p_m^d - p_{ri}^d - c_{ri})^2\delta_b^2] \quad (14)$$

$$U(\pi^d) = U(\pi_m^d) + \sum_{i=1}^{2} U(\pi_{ri}^d) \tag{15}$$

4.2. Centralized Control Decision-Making Model

In the process of centralized control decision-making, the CLSC is an idealized "super-organization" with the goal of maximizing the sum of profits of each member company in the CLSC. At this point, the manufacturer and the two retailers face the sales market and the recycling market as a combined unit. The manufacturer's wholesale price and recycling price are treated as internal transfer prices, which affect the profit of each participant, but do not affect the total profit of the system. The total profit of the system is determined by the retailer's selling price, recycling price, and related costs. The wholesale price and recycling price determined by the manufacturer are an effective way of coordinating the relationships among the system participants. Based on the perceived risks and benefits, the system selects the appropriate sales price p_i^c and recycling price p_{ri}^c to maximize the utility function of the entire supply chain. The utility function of the supply chain as a whole can be expressed as:

$$\begin{aligned} U(\pi^c) = \sum_{i=1}^{2} \{ (p_i - c_m - c_i)\overline{D}_i + (c_m - c_{mz} - c_{ri} - p_{ri})\overline{Q}_i - \eta_r (p_i - w_m - c_i)^2 \delta_a^2 \\ -\eta_r (p_m - p_{ri} - c_{ri})^2 \delta_b^2 - \eta_m [(w_m - c_m)^2 \delta_a^2 + (c_m - c_{mz} - p_m)^2 \delta_b^2] \Big\} \end{aligned} \tag{16}$$

In accordance with the necessary conditions for the first-order optimal, p_i and p_{ri} are obtained as follows:

$$\partial U(\pi^c)/\partial p_i = \overline{a} + (\beta - \gamma)(c_m + c_r) + 2\eta_r \delta_a^2 (w_m + c_r) - (2\beta - 2\gamma + 2\eta_r \delta_a^2) P_i$$

$$\partial U(\pi^c)/\partial p_{ri} = (h - \lambda)(c_m - c_{mz} - c_{rz}) + 2\eta_r \delta_b^2 (p_m - c_{rz}) - \overline{b} - (2h - 2\lambda + 2\eta_r \delta_b^2) p_{ri}$$

Since $\partial^2 U(\pi)/\partial {p_i}^2 = -(2\beta - 2\gamma + 2\eta_r \delta_a^2) < 0$ and $\partial^2 U(\pi)/\partial {p_{ri}}^2 = -(2h - 2\lambda + 2\eta_r \delta_b^2) < 0$, let $\partial U(\pi)/\partial p_i = 0$ and $\partial U(\pi)/\partial p_{ri} = 0$. Then, we can obtain the optimal sales price p_i^c and waste recycling price p_{ri}^c determined by the retailer under centralized decision-making as follows:

$$p_i^c = [\overline{a} + (\beta - \gamma)(c_m + c_r) + 2\eta_r \delta_a^2 (w_m + c_r)] / (2\beta - 2\gamma + 2\eta_r \delta_a^2)(i = 1, 2) \tag{17}$$

$$p_{ri}^c = [(h - \lambda)(c_m - c_{mz} - c_{rz}) + 2\eta_r \delta_b^2 (p_m - c_{rz}) - \overline{b}] / (2h - 2\lambda + 2\eta_r \delta_b^2)(i = 1, 2) \tag{18}$$

Next, we substitute p_i^c and p_{ri}^c into the utility function $U(\pi^c)$ and let $\partial U(\pi^c)/\partial w_m = 0$ and $\partial U(\pi^c)/\partial p_m = 0$. Thus, the optimal wholesale price w_m^c and the recycling price p_m^c determined by the manufacturer under centralized decision-making can be obtained as follows:

$$w_m^c = \frac{\eta_r [\overline{a} - (\beta - \gamma)(c_m + c_r)]}{2\eta_r (\beta - \gamma) + 2\eta_m (\beta - \gamma + \eta_r \delta_a^2)} + c_m \tag{19}$$

$$p_m^c = \frac{\eta_r [(h - \lambda)(c_{mz} + c_{rz} - c_m) - \overline{b}]}{2\eta_r (h - \lambda) + 2\eta_m (h - \lambda + \eta_r \delta_b^2)} + (c_m - c_{mz}) \tag{20}$$

Proposition 3. *Given the risk aversion factors η_r and η_m, we obtain:*

$$w_m^c < w_m^d \text{ and } p_m^c > p_m^d$$

Proof. Let $A_1 = \overline{a} - (\beta - \gamma)(c_m + c_r)$, $A_2 = -[\overline{b} + (c_m - c_{mz} - c_{rz})(h - \lambda)]$, $B_1 = \eta_r(\beta - \gamma) + \eta_m(\beta - \gamma + \eta_r \delta_a^2)$, $B_2 = \eta_r(h - \lambda) + \eta_m(h - \lambda + \eta_r \delta_b^2)$, $C_1 = (\beta - \gamma)(\beta + 2\eta_r \delta_a^2) + \eta_m \delta_a^2 (2\beta - \gamma + 2\eta_r \delta_a^2)$, and $C_2 = (h - \lambda)(h + 2\eta_r \delta_b^2) + \eta_m \delta_b^2 (2h - \lambda + 2\eta_r \delta_b^2)$.

Since $p_i > w_m + c_r > c_m + c_r$ and $D_i = a - \beta p_i + \gamma p_{3-i} > 0$, we obtain:

$$A_1 > 0.$$

Further, since $c_m - c_{mz} > p_m$, $p_m > p_{ri} + c_{ri}$, and $Q_i = b + h p_{ri} - \lambda p_{r(3-i)} > 0$, we obtain:

$$A_2 < 0.$$

At the same time, it is easy to know the size relationship of variables $B_1 > 0$, $B_2 > 0$, $C_1 > 0$, and $C_2 > 0$. Subtracting w_m^d from w_m^c and p_m^d from p_m^c, we obtain the following relationships:

$$w_m^c - w_m^d = -[A_1 * \eta_m(\beta - \gamma)(\beta + \eta_r \delta_a^2)]/(2B_1 * C_1) < 0 \quad (21)$$

$$p_m^c - p_m^d = -[A_2 * \eta_m(h - \lambda)(h + \eta_r \delta_b^2)]/(2B_2 * C_2) > 0 \quad (22)$$

Proposition 3 shows that under centralized decision-making, the wholesale price of the manufacturer is lower than that under decentralized decision-making, while the recycling price is higher than that under decentralized decision-making.

Proposition 4. *In centralized decision-making, the wholesale price w_m^c of the optimal product determined by the manufacturer is negatively correlated with their risk aversion coefficient η_m and positively correlated with the retailer's risk aversion coefficient η_r, while the recycling price p_m^c is positively correlated with the manufacturer's risk aversion coefficient η_m and negatively correlated with the retailer's risk aversion coefficient η_r.*

Proof. w_m^c and p_m^c are derived from the risk aversion coefficients η_m and η_r, respectively:

$$\frac{\partial w_m^c}{\partial \eta_m} = \frac{-2\eta_r[\overline{a} - (\beta - \gamma)(c_m + c_r)] \times (\beta - \gamma + \eta_r \delta_a^2)}{[2\eta_r(\beta - \gamma) + 2\eta_m(\beta - \gamma + \eta_r \delta_a^2)]^2} \quad (23)$$

$$\frac{\partial w_m^c}{\partial \eta_r} = \frac{2\eta_m(\beta - \gamma)[\overline{a} - (c_m + c_r)(\beta - \gamma)]}{[2\eta_r(\beta - \gamma) + 2\eta_m(\beta - \gamma + \eta_r \delta_a^2)]^2} \quad (24)$$

$$\frac{\partial p_m^c}{\partial \eta_m} = \frac{2\eta_r[\overline{b} + (h - \lambda)(c_m - c_{mz} - c_{rz})] \times (h - \lambda + \eta_r \delta_b^2)}{[2\eta_r(h - \lambda) + 2\eta_m(h - \lambda + \eta_r \delta_b^2)]^2} \quad (25)$$

$$\frac{\partial p_m^c}{\partial \eta_r} = \frac{-2\eta_m(h - \lambda)[\overline{b} + (c_m - c_{mz} - c_{rz})(h - \lambda)]}{[2\eta_r(h - \lambda) + 2\eta_m(h - \lambda + \eta_r \delta_b^2)]^2} \quad (26)$$

Similar to Proposition 1, we obtain:

$$\partial w_m^c/\partial \eta_m < 0,\ \partial w_m^c/\partial \eta_r > 0, \partial {p_m}^c/\partial \eta_m > 0, \text{ and } \partial p_m^c/\partial \eta_r < 0.$$

Substituting w_m^c and p_m^c into Equations (17) and (18), we can obtain the optimal selling price p_i^c and the recycling price p_{ri}^c determined by the retailer. Furthermore, under centralized control decision-making, the value of the utility function of the supply chain as a whole can be expressed as:

$$\begin{aligned} U(\pi^c) = \sum_{i=1}^{2} \Big\{ & (p_i^c - c_m - c_i)\overline{D}_i + (c_m - c_{mz} - c_{ri} - p_{ri}^c)\overline{Q}_i - \eta_r (p_i^c - w_m^c - c_i)^2 \delta_a^2 \\ & - \eta_r (p_m^c - p_{ri}^c - c_{ri})^2 \delta_b^2 - \eta_m [(w_m^c - c_m)^2 \delta_a^2 + (c_m - c_{mz} - p_m^c)^2 \delta_b^2] \Big\} \end{aligned} \quad (27)$$

4.3. Revenue-Sharing Contract Coordination Model

A revenue-sharing contract generally involves the manufacturer providing a suitable wholesale price to the retailer, who pays a certain percentage of their sales revenue to the manufacturer to facilitate both risk sharing and profit sharing among the members. However, in the CLSC, the retailer's revenue includes product sales revenue and waste recycling revenue. Therefore, the revenue-sharing contract coordination mechanism in the CLSC is that the manufacturer provides the retailer with a suitable wholesale price w_m and recycling price p_m, and then the retailer pays sales revenue and recycling revenue to the manufacturer in a certain proportion $(1-s)$. At this point, the utility functions of the manufacturer and retailer can be expressed as:

$$\begin{aligned} U(\pi_m^o) = \sum_{i=1}^{2} \{ & [(1-s)p_i + w_m - c_m]\overline{D}_i + [(1-s)p_m + c_m - c_{mz} - p_m]\overline{Q}_i \\ & -\eta_m[(1-s)p_i + w_m - c_m]^2\delta_a^2 - \eta_m(c_m - c_{mz} - sp_m)^2\delta_b^2] \} \end{aligned} \quad (28)$$

$$\begin{aligned} U(\pi_{ri}^o) = & (sp_i - w_m - c_i)\overline{D}_i + (sp_m - p_{ri} - c_{ri})\overline{Q}_i \\ & -\eta_r[(sp_i - w_m - c_i)^2\delta_a^2 + (sp_m - p_{ri} - c_{ri})^2\delta_b^2] \end{aligned} \quad (29)$$

In accordance with the necessary conditions for the first-order optimal, p_i and p_{ri} are given by:

$$\partial U(\pi_{ri}^o)/\partial p_i = s\overline{a} + (\beta + 2s\eta_r\delta_a^2)(w_m + c_r) - (2s\beta - s\gamma + 2s^2\eta_r\delta_a^2)p_i \quad (30)$$

$$\partial U(\pi_{ri}^o)/\partial p_{ri} = (sp_m - c_{ri})(h + 2\eta_r\delta_b^2) - \overline{b} - (2h - \lambda + 2\eta_r\delta_b^2)p_{ri}. \quad (31)$$

Since $\partial^2 U(\pi_{ri}^o)/\partial {p_i}^2 = -(2s\beta - s\gamma + 2s^2\eta_r\delta_a^2) < 0$ and $\partial^2 U(\pi_{ri}^o)/\partial {p_{ri}}^2 = -(2h - \lambda + 2\eta_r\delta_b^2) < 0$, let $\partial U(\pi_{ri}^o)/\partial p_i = 0$ and $\partial U(\pi_{ri}^o)/\partial p_{ri} = 0$. We can obtain the optimal sales price p_i^o and the optimal recycling price p_{ri}^o under the revenue-sharing contract as follows:

$$p_i^o = [s\overline{a} + (\beta + 2s\eta_r\delta_a^2)(w_m + c_r)]/(2s\beta - s\gamma + 2s^2\eta_r\delta_a^2)(i = 1,2) \quad (32)$$

$$p_{ri}^o = [(sp_m - c_{ri})(h + 2\eta_r\delta_b^2) - \overline{b}]/(2h - \lambda + 2\eta_r\delta_b^2)(i = 1,2) \quad (33)$$

If the revenue-sharing contract can facilitate the coordination of the CLSC, the retailer's optimal selling price and optimal waste product recycling price under the contract are consistent with those under centralized control decision-making. That is, $p_i^o = p_i^c$ and $p_{ri}^o = p_{ri}^c$. Thus, in a revenue-sharing contract, the optimal wholesale price w_m^o and recycling price p_m^o determined by the manufacturer can be expressed as:

$$w_m^o = \frac{\begin{array}{c}(s\overline{a} + 2s\eta_r\delta_a^2 c_r)[(2-2s)\eta_r\delta_a^2 - \gamma] + \beta c_r(2\beta - 2\gamma + \\ 2\eta_r\delta_a^2) - (\beta - \gamma)(c_m + c_r)(2s\beta - s\gamma + 2s^2\eta_r\delta_a^2)\end{array}}{2s\eta_r\delta_a^2[(2s-2)\eta_r\delta_a^2 + \gamma] - \beta(2\beta - 2\gamma + 2\eta_r\delta_a^2)} \quad (34)$$

$$p_m^o = \frac{[(h-\lambda)(c_m - c_{mz}) + \lambda c_{rz}](2h - \lambda + 2\eta_r\delta_b^2) - \lambda(\overline{b} + 2\eta_r\delta_b^2 c_{rz} + c_{rz}h)}{s(h + 2\eta_r\delta_b^2)(2h - 2\lambda + 2\eta_r\delta_b^2) - 2\eta_r\delta_b^2(2h - \lambda + 2\eta_r\delta_b^2)} \quad (35)$$

Substituting w_m^o and p_m^o into Equations (32) and (33), we can obtain the optimal selling price p_i^o and recycling price p_{ri}^o determined by the retailer. Furthermore, under the revenue-sharing contract, the utility function values of the manufacturer, the retailers, and supply chain as a whole can be expressed as:

$$\begin{aligned} U(\pi_m^o) = \sum_{i=1}^{2} \{ & [(1-s)p_i^o + w_m^o - c_m]\overline{D}_i + [(1-s)p_m^o + c_m - c_{mz} - p_m^o]\overline{Q}_i \\ & -\eta_m[(1-s)p_i^o + w_m^o - c_m]^2\delta_a^2 - \eta_m(c_m - c_{mz} - sp_m^o)^2\delta_b^2] \} \end{aligned} \quad (36)$$

$$U(\pi_{ri}^o) = (sp_i^o - w_m^o - c_i)\overline{D}_i + (sp_m^o - p_{ri}^o - c_{ri})\overline{Q}_i \\ -\eta_r[(sp_i^o - w_m^o - c_i)^2\delta_a^2 + (sp_m^o - p_{ri}^o - c_{ri})^2\delta_b^2] \tag{37}$$

$$U(\pi^o) = U(\pi_m^o) + \sum_{i=1}^{2} U(\pi_{ri}^o) \tag{38}$$

Implementation of a revenue-sharing contract should also ensure that the utility functions of the manufacturer and the two retailers are no lower than those under decentralized decision-making. Therefore, manufacturers must meet the following conditions when contracting with retailers:

$$U(\pi_m^o) \geq U(\pi_m^d),\ U(\pi_{ri}^o) \geq U(\pi_{ri}^d) \tag{39}$$

By substituting the specific parameter values into Equation (39), the proportional coefficient for the revenue-sharing contract between the manufacturer and the retailers can be obtained.

5. Numerical Analysis

To validate the proposed models and derive management implications, we utilize the illustrative example from Huawei in Section 4 for a numerical experiment. Using Huawei's mobile phone manufacturing and remanufacturing data, as well as their mobile phone sales and recycling data for Changsha, we obtain the following specific parameter values: $c_m = 30$, $c_{mz} = 10$, $c_r = 5$, $c_{rz} = 2$, $\beta = 15$, $\gamma = 10$, $h = 20$, $\lambda = 15$, $\overline{a} = 800$, $\delta_a = 5$, $\overline{b} = 50$, and $\delta_b = 2$.

After considering the impact of risk aversion on the decisions of the manufacturer and the retailers, we set η_m and η_r to a step size of 0.1 and a variation interval of [0, 1]. By substituting the above parameters into Equations (7), (8), (19), and (20), the relationship between the wholesale price w_m, recycling price p_m, and the risk aversion coefficient η_m, η_r under decentralized decision-making and centralized control decision-making can be obtained, as shown in Figures 1 and 2.

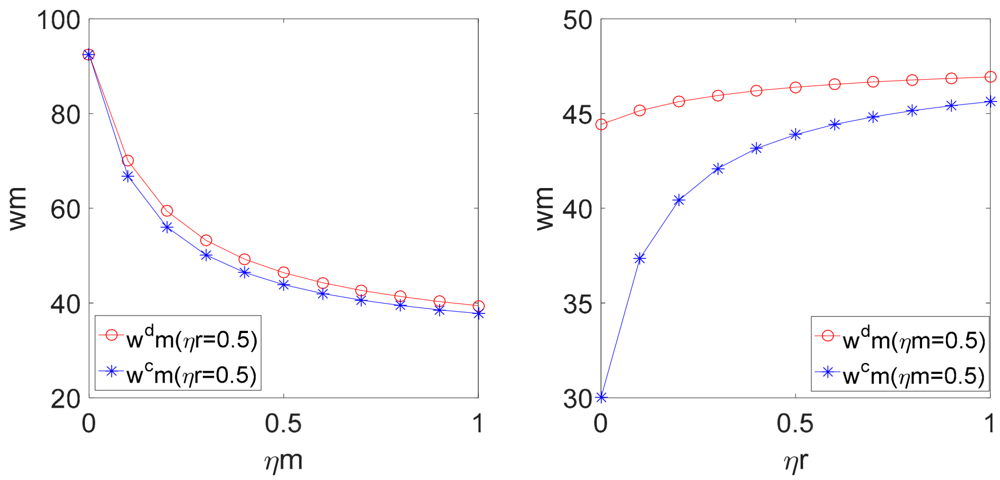

Figure 1. Relationship between ${w_m}^d$ and ${w_m}^c$, and η_m and η_r.

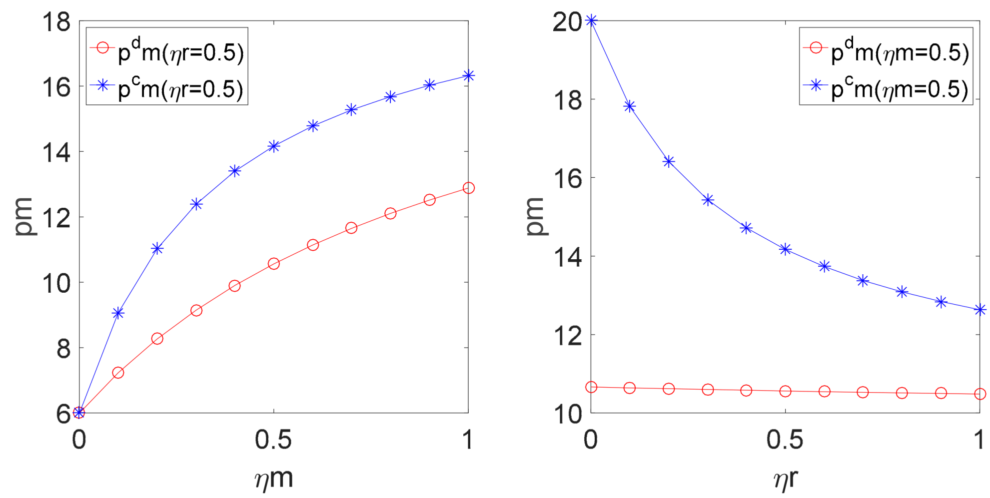

Figure 2. Relationship between ${p_m}^d$ and ${p_m}^c$, and η_m and η_r.

It can be seen from Figure 1 that the wholesale price w_m under decentralized decision-making is higher than that under centralized control decision-making. The wholesale price w_m increases as the retailer's risk aversion coefficient η_r increases and decreases as the manufacturer's risk aversion coefficient η_m increases. This can be understood as a strategy aimed at reducing the wholesale price to reduce risk when the manufacturer's risk aversion factor is high. It can be seen from Figure 2 that the recycling price p_m under centralized control decision-making is significantly higher than that under decentralized decision-making. The recycling price p_m decreases as the retailer's risk aversion coefficient η_r increases and increases as the manufacturer's risk aversion coefficient η_m increases. This can be understood as a strategy aimed at increasing the recycling price to increase revenue when the manufacturer's risk aversion factor is high.

By substituting the above parameters into Equations (5) and (6), the relationships between the selling price p_i, recycling price p_{ri}, and risk aversion coefficients η_m, and η_r under decentralized decision-making can be obtained, as shown in Figures 3 and 4.

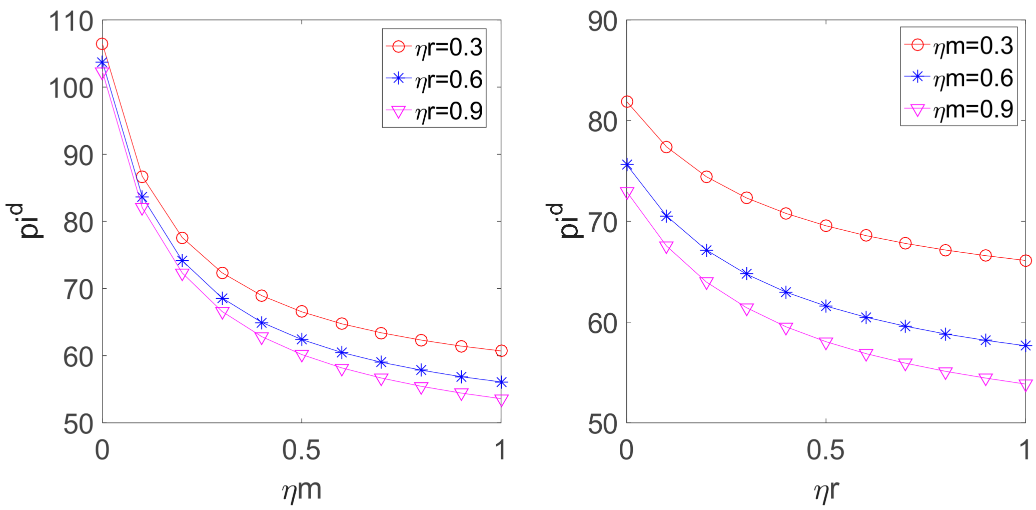

Figure 3. Relationship between ${p_i}^d$ and η_m, η_r.

It can be seen from Figures 3 and 4 that under decentralized decision-making, the retailer's selling price p_i decreases with an increase in the retailer's risk aversion coefficient η_r and the manufacturer's risk aversion coefficient η_m. This can be understood as a strategy aimed at reducing the selling price to reduce the risk when the overall risk aversion coefficient of the supply chain is high. At the same time, the retailer's recovery price p_{ri} increases as the retailer's risk aversion factor η_r and the manufacturer's risk aversion factor η_m increase. This can be understood as a strategy aimed at increasing the recovery price to increase the revenue of the entire chain when the overall risk aversion factor of the supply chain is high. Although the risk aversion coefficient has the same trend for p_i and p_{ri}, by comparing the impact of η_r and η_m on the price, it can be seen that the influence of η_r and η_m is inconsistent. Under the same conditions, η_m has a greater impact on p_i and p_{ri}.

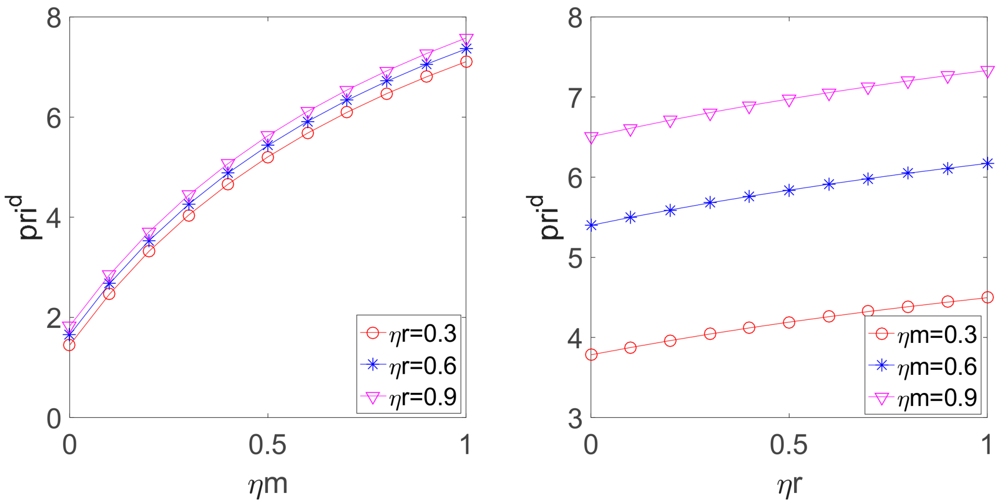

Figure 4. Relationship between ${p_{ri}}^d$ and η_m, η_r.

By substituting the above parameters into Equations (17) and (18), the relationship between the selling price p_i, recycling price p_{ri}, and risk aversion coefficients η_m and η_r under centralized control decision-making can be obtained, as shown in Figures 5 and 6.

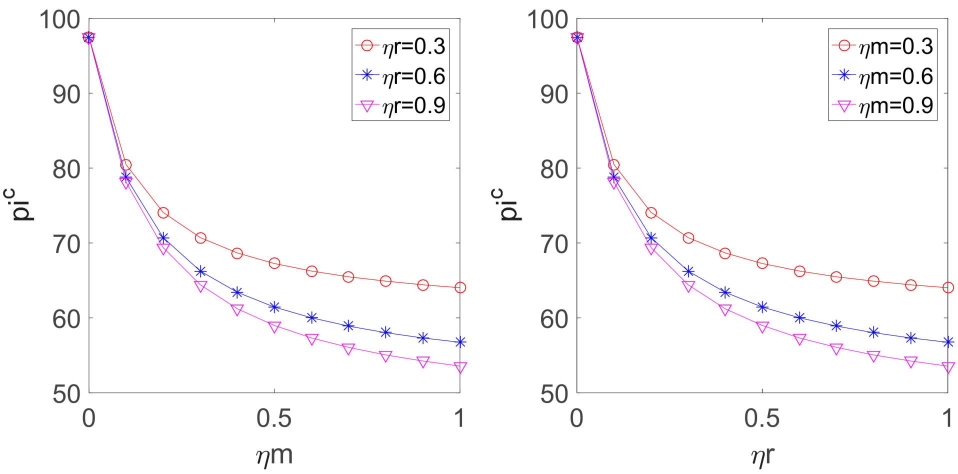

Figure 5. Relationship between ${p_i}^c$ and η_m and η_r.

As can be seen from Figures 5 and 6, under centralized control decision-making, the retailer's sales price p_i decreases as η_r and η_m increase and their recovery price p_{ri} increases as η_r and η_m increase. Comparing the impact of η_r and η_m on the prices, it can be seen that η_r and η_m have the same degree of influence on the prices. This can be understood as a strategy aimed at lowering the selling price and increasing the recycling price to reduce the risk to the overall system when the decision is made centrally, and the system responds as a whole regardless of which party initiates the risk avoidance behavior. Therefore, η_r and η_m have the same degree of influence on p_i and p_{ri}.

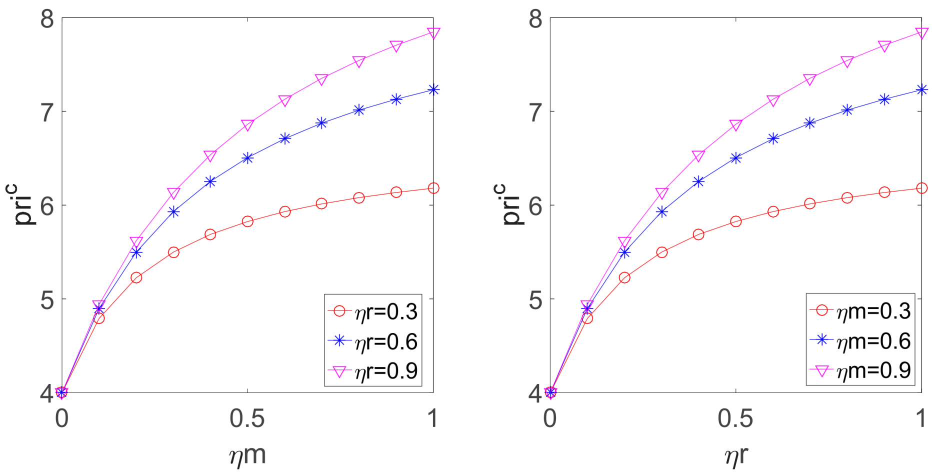

Figure 6. Relationship between ${p_{ri}}^c$ and η_m and η_r.

By fixing $\eta_r = 0.4$ and $\eta_m = 0.6$, we can obtain utility values for the manufacturer and retailers under both decentralized decision-making and centralized decision-making, as shown in Table 1.

Table 1. Comparison of profit distribution among supply chain members. (under different decision-making scenarios).

Decision Process	$2\pi_r$	π_m	π	η_r	η_m
decentralized decision	10,095.578	8718.342	18,813.92	0.4	0.6
centralized decision			19,396.1046	0.4	0.6

In the case of a contract, the specific value of the income distribution coefficient s depends on the game ability between the manufacturer and the retailer. This is generally negotiated based on their respective contributions to the entire supply chain. As long the conditions of Equation (39) are met, the retailers' and manufacturer's returns will be higher than those under decentralized decision-making.

6. Conclusions

In this study, we examine a CLSC under the condition of a competitive product market and recycling market. The CLSC consists of one risk-averse manufacturer and two risk-averse retailers who compete in terms of both retail prices and recycling prices. The manufacturer and retailers conduct a manufacturer-led Stackelberg game. The manufacturer decides on the optimal wholesale price and recycling price, while the retailers decide on their optimal selling price and recycling price. We examine the effects of the risk aversion coefficient on the players' decisions.

Our results show that under decentralized decision-making, the pricing decisions of the manufacturer and retailers are affected not only by their own risk aversion coefficient but also by the other parties' risk aversion coefficients, although under given conditions, the manufacturer's risk aversion coefficient has a greater impact on pricing decisions. Under centralized decision-making, the risk aversion coefficient also affects pricing decisions, but the different types of risk aversion coefficients have the same level of impact on pricing. Comparative analysis shows that the wholesale price under centralized decision-making is lower than that under decentralized decision-making, while the recovery price is higher than that under decentralized decision-making. To achieve CLSC coordination, a revenue-sharing contract coordination model is constructed, which can benefit all supply chain members through appropriate revenue-sharing coefficients. Our results provide insights into the relationship between risk aversion features and pricing in sustainable closed-loop supply chains (SCLSC), which is rarely studied in the references to our best of knowledge. This study helps managers and decision-makers of SCLSC to choose the most effective revenue-sharing strategy in the face of risk aversion characteristics and to coordinate the benefit distribution process to optimize overall system revenue.

For the sake of simplification without loss of generality, some assumptions are made in this study that can be regarded as our extended research directions. First, we assume that the cost of sales and the recycling costs of the two retailers are identical. However, the two costs may be different among competitive retailers in some cases. Second, the demand function is a simple linear form related to price. A nonlinear demand function involving competitive manufacturers may be more realistic.

Author Contributions: H.Z. wrote the manuscript and participated in all phases. J.Q. supervised the whole research work and provided constructive suggestions to improve the research and manuscript. P.Y. investigated the data for the experiments. B.D. proposed the research problem, involved in model development. All authors have read and approved the final manuscript.

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