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WHAT IS THE ROLE OF PRODUCT SERVICES IN THE DUAL-CHANNEL CLOSED-LOOP SUPPLY CHAIN?

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Abstract. With the continuous development of internet technology and increasing awareness of environmental protection among consumers, the dual-channel closed-loop supply chain management combining online direct sales channel and retail channel has received more and more attention, however, the existing research has neglected the service research, so this paper focuses on the service strategy in the dual-channel closed-loop supply chain. In this paper, we propose three service strategy models for dual-channel closed-loop supply chains, including when there is no service provision, after-sales service and recycling service provided by retailers and after-sales service provided by manufacturers and recycling service provided by retailers, compare and analyze the optimal decisions of supply chain members under the three service strategy models, discuss the role of service generated in dual-channel closed-loop supply chains, and propose a service cost-sharing strategy to achieve a Pareto improvement in the effectiveness of a dual-channel closed-loop supply chain. The study finds that service plays a positive role in the dual-channel closed-loop supply chain; the model of manufacturer providing after-sales service and retailer providing recycling service is the best service strategy choice in terms of economic and social benefits; the service cooperation mechanism of service cost sharing can achieve Pareto improvement of the supply chain within a reasonable range.

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1. Introduction

With the development of the world economy, on the one hand, a large amount of non-renewable energy and resources are being expedited. On the other hand, a large number of waste products and packaging materials have seriously aggravated environmental pollution. To a certain extent, environmental and resource issues have hindered the path of sustainable development. For enterprises, under the circumstances where raw material resources are becoming more difficult to obtain and product life cycles are becoming shorter and shorter, a more effective way to solve the pressure of environmental regulation and competition is to recycle and remanufacture waste products. Companies are actively engaging in recycling and remanufacturing activities to create closed-loop supply chains and benefit from the circular economy [26]. To recycle the waste products remanufacturing can reduce the manufacturing cost of the enterprise [12]. For example, large companies such as Xerox, Kodak, and IBM have gained huge economic benefits in the process of recycling and remanufacturing, making companies

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more proactive in recycling waste products and forming closed-loop supply chain systems. In addition, with the rapid development of e-commerce and the increasing diversification of consumer demand, market competition is getting fiercer. The supply chain model of dual channel sales has gradually replaced the traditional single-channel sales model and become the main sales method of most manufacturers [31]. For example, BIM, Apple, Nike have established dual-channel sales channel. Enterprises in traditional retail channels can provide consumers with a high-quality physical shopping experience and high-quality physical services due to the materialization of their stores, the real-time and face-to-face services; In the online direct sales channel, products may be more abundant and diverse, and consumers search for products without time and space restrictions, which greatly reduces consumers' product search costs.

As consumers' demand for services increases, consumers pay more and more attention to product service provision when making product purchase or recycling decisions. In the face of this situation, companies pay more attention to the after-sales service and the recycling service that they provide. In this article, after-sales services refer to the logistics services, installation services, maintenance services and other services provided by the merchant after the product is sold, while recycling services refer to door-to-door recycling services, free disassembly services and other services provided by merchants before the recycling of waste products is completed. For example, Haier companies that implement closed-loop supply chain management provide customers with a series of after-sales services such as storage and installation, effectively improving customer satisfaction. Suning, China's largest home appliance retailer, also provides consumers with various after-sales services, as well as door-to-door recycling and quality inspection services for home appliances and electronic products. Therefore, product service has become one of the important ways to enhance the competitiveness of enterprises, and it is also one of the important factors affecting consumers' purchasing decisions [11, 35].

However, the literature on the DCCLSC management seldom pays attention to the role of service. In practice, we have found that product services can be provided by different closed-loop supply chain members. Therefore, this article takes the service strategy in the DCCLSC as the research focus, and explores how different supply chain members will affect the decision-making results when they provide services. The purpose of this paper is to analyze the role of service in the DCCLSC, explore reasonable service strategies to better exert the positive influence of service decision-making on the decision-making of supply chain members and supply chain efficiency, and achieve Pareto improvement. This article attempts to clarify the following issues: Q1: What is the role of service in a DCCLSC, and how does it affect the decision-making of supply chain members? Q2: In the context of the retailer providing recycling services, who is more suitable to provide after-sales service in a DCCLSC, the manufacturer or the retailer? Q3: How to optimize the performance of the DCCLSC through service cooperation strategies and achieve Pareto improvement?

Based on this, this article proposes three dual-channel closed-loop supply chain service strategy models, including no service provision (Model), the retailer providing after-sales service and recycling service (Model), the manufacturer providing after-sales service and the retailer providing recycling service (Model), contrasts and analyzes the optimal decision-making and profit results of supply chain members under the three service strategy models, and discusses the role of service in the DCCLSC. In addition, we also propose a Pareto-improved service strategy for the DCCLSC–service cost sharing strategy to achieve supply chain optimization. This article aims to provide a theoretical basis for enterprises that adopt DCCLSC management when making service decisions.

The main contributions of this paper are as follows: (1) This article introduces service into the DCCLSC system. When the service has a positive impact on product demand and the recycling volume of waste products, we analyze the role of service in the DCCLSC management and discover the service plays an active role in the DCCLSC system. Supply chain members can improve their own revenue services by adjusting service levels; (2) We compare and analyze different service strategies, and conclude that the best service delivery mode is that the manufacturer provides after-sales service and the retailer provides recycling services; (3) On the basis of obtaining the optimal service strategy, we propose a service cooperation mechanism based on service cost sharing and show that under a certain cost sharing ratio, the efficiency of the supply chain can be optimized and improved.

The rest of the paper is organized as follows: in Section 2, the current state of the literature research related to this paper is outlined and reviewed. In Section 3, the main model structure and market context of this paper are constructed, and the important variables and functions are specified. Section 4 includes model solving and mathematical analysis. In Section 5, the equilibrium results of the models obtained in Section 4 are compared and analyzed, as well as the sensitivity analysis of the important parameters. In Section 6, we propose a service cooperation strategy with service cost sharing. The last section summarizes the main work and important conclusions of this paper.

2. Literature review

In recent years, sustainable production and consumption have received increasing attention and there has been a proliferation of research on the circular economy. There are three methods to achieve circular economy in the supply chain [3, 22, 26, 29]: reverse supply chain, open-loop supply chain and closed-loop supply chain. Among them, the closed-loop supply chain plays a vital role in the circular economy. This is because the closed-loop supply chain focuses on both the forward sales activities of products and the reverse recycling and reuse of used products, which has the goal of reducing costs and promoting sustainable development [27]. The circular economy of remanufacturing has been widely concerned, and the cost saving brought by remanufacturing also brings more profits and benefits to enterprises. Many scholars pay attention to closed-loop supply chain management [34]. Existing researches mainly analyze the influence of recovery mode, recovery contract and other aspects on the decision-making of supply chain members and the profit of supply chain [1,2,10,15,24,29]. At the same time, with the continuous development of Internet technology, many manufacturing enterprises expand their sales channels through online direct sales. Manufacturers sell products through the dual-channel model combining online direct sales channels with offline retail channels. Dual-channel supply chain system is becoming more and more common [23, 31]. Due to the homogeneity of sales products, compared with the single-channel sales, the addition of manufacturers' online direct channels divides the market share of retailers, causes channel conflicts and intensifies the competition contradiction between manufacturers and retailers [25, 36]. But in fact, the introduction of dual-channel will also bring some positive effects to supply chain members [18, 30], and dual-channel model is more favored by consumers. At present, research on dual channel supply chain as the analysis object a lot, including the selection of dual-channel channel structure [13, 37], inventory level decision [9], green level decision [14], etc. Therefore, with the continuous development of internet technology and the increasing consumer awareness of environmental protection, the dual-channel closed-loop supply chain management that combines online direct sales channels and retail channels has received more and more attention.

In research and practice, we have found that services also play an increasingly important role, and even become an important factor in determining consumer channel choices [7]. Services play an important role in supply chain decision-making [20, 21, 33, 40]. Most of the research is carried out under the traditional supply chain structure or dual-channel supply chain structure and is more inclined to study the situation where retailers provide services or there is service competition. Wang *et al.* [32] constructed a research model of manufacturers and online platforms for sales and recycling, and explored the mechanism of the impact of online services on the operation of e-commerce supply chains, and increasing consumer sensitivity to online services is always beneficial to each member of the supply chain. Zhang *et al.* [41] studied the warranty service outsourcing strategy in the dual-channel supply chain, including the retailer providing warranty services or the third-party providing warranty services. By comparing different outsourcing strategies, the best solution was proposed to achieve a "win-win" situation for the manufacturer and the retailer. Hong *et al.* [17] took the dual-channel supply chain as the main research body to discover the important role of value-added services in the dual-channel supply chain. Dan *et al.* [6] found that when there was service competition between the manufacturer and the retailer, the differentiation strategy of value-added services would affect the profits of supply chain members and supply chain profits. Gallego *et al.* [8] found that in the integration model of online sales and offline services, low channel service levels would put pressure on offline channels. Dan *et al.* [5]studied the role of the services provided by the retailer to products in the context of dual channels, and found that the service level of retailers was affected by

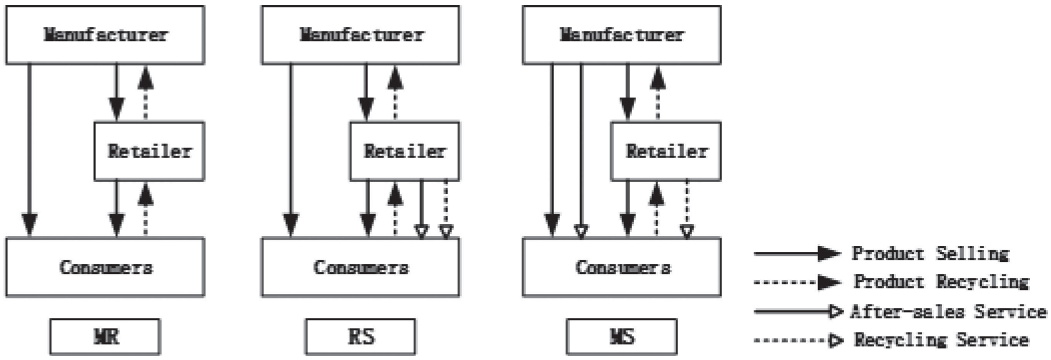


FIGURE 1. Three schemes of dual-channel closed-loop supply chain.

consumers' loyalty to retail channels. At the same time, in the reverse recycling channel of the closed-loop supply chain, investment research on the reverse channel is more focused on advertising and publicity, ignoring the role of recycling services. Xie *et al.* [35] considered the closed-loop supply chain coordination problem of recycling advertising investment, and proposed that by adopting a reasonable recycling cost sharing and recycling revenue sharing ratio, the recycling rate of waste products could be improved. Yi *et al.* [38] constructed a game model in which advertising affects demand, and discussed optimal pricing, advertising investment, and coordination decisions among supply members.

Most of the existing studies are in the context of retailers providing services, or in the traditional supply chain or in the dual-channel supply chain. The focus of the research is more on the forward channel services. However, service providers should not be limited to the retailer only, other members of the supply chain can also assume this responsibility. At the same time, in combination with the current social background, the role of research services in the DCCLSC is more significant. In reality, companies' investment in reverse channels is not just about advertising. Consumers who are increasingly concerned about product services will also expect the level of service brought by reverse channels. Companies can improve the product recycling process and increase the revenue of reverse channels by providing consumers with door-to-door recycling and other services. In this article, we add after-sales service and recycling services to the DCCLSC system, discuss different service delivery strategies, and propose a service cooperation mechanism between manufacturers and retailers to improve supply chain efficiency.

3. Model description and notations

The DCCLSC system studied in this paper is composed of a single manufacturer and a single retailer, as shown in Figure 1. This paper constructs three different service strategy research models for DCCLSC. In the MR model, the manufacturer is responsible for product manufacturing/remanufacturing, online direct sales of products to consumers, and wholesale products to the retailer, and the retailer is responsible for the wholesale of products from the manufacturer to consumers for offline sales and the recycling of waste products and then transfer to the manufacturer, and there is no service provision in this model. In the RS model, the manufacturer is responsible for product manufacturing/remanufacturing, online direct sales of products to consumers, and wholesale products to the retailer, and the retailer is responsible for the wholesale of products from the manufacturer to consumers for offline sales and the recycling of waste products and then transfer to the manufacturer and providing after-sales service and recycling services for products to consumers. In the MS model, the manufacturer is responsible for product manufacturing/remanufacturing, online direct sales of products to consumers, wholesale products to the retailer, and providing after-sales service to consumers, and the retailer is responsible for the wholesale of products from the manufacturer to consumers for offline sales, the recycling of waste products and then transferring to the manufacturer and providing recycling services for products to consumers.

In this paper, a manufacturer is considered to play a Stackelberg game with a retailer in a decentralized decision. Assuming that the manufacturer is in a dominant position in the closed-loop supply chain system, the manufacturer makes the decision first, and the retailer makes the corresponding decision based on the manufacturer's actions.

3.1. Parameter settings

The parameters involved in this paper are shown in Table 1. In the analysis process, the superscript * represents the optimal decision and income under the decentralized decision model.

3.2. Model assumptions

Assumption 3.1. *This article only considers the single-cycle decision-making model, that is, assuming that the sales products in the previous stage already exist in the market, in the current cycle to study the impact of manufacturer's and retailer's pricing and service strategies on supply chain profits.*

Assumption 3.2. *Assuming that the information of the manufacturer and the retailer is completely symmetrical, the capacity of the manufacturer is sufficient to meet the market demand. The new products produced by the manufacturer are consistent with the quality of the remanufactured products and are wholesale to the retailer at the same price. Consumers accept the same degree of new products and remanufactured products, and a consumer can only choose one channel at most and only buy one product.*

Assumption 3.3. *Remanufacturing is a process of complete dismantling, cleaning, parts repair, and reassembly on the basis of waste products. The cost savings per unit of raw materials are related to the quality of recycling of waste products. While the remanufacturing process saves raw materials, it also incurs remanufacturing costs. This paper is concerned with the situation where the unit cost required to produce a remanufactured product from a used product is lower than the unit cost required for a new product. Suppose the production cost of new products is c_m, then the production cost of remanufactured products is $(1-k)c_m$, $k \in (0,1)$. k represents the quality coefficient of recycled products. The cost savings from remanufacturing can also be obtained as kc_m [4, 16, 17].*

Assumption 3.4. *This article assumes that the impact of service on consumer choices exceeds the effect of price changes on consumer choices, and that consumers in the retail channel pay more attention to service quality than consumers in the online direct sales channel.*

3.3. Function definition

3.3.1. Demand function

Prices and services are important factors influencing consumers' purchasing decisions. This article considers that market demand is mainly affected by the direct sales price of the online direct sales channel, retail prices of the retail channel, and service levels of the retail channel. The service level of the recycling channel only affects the recycling volume of the reverse channel, and does not consider the impact on the market demand of the forward channel. Drawing on the linear demand function of Dan *et al.* [5], this article defines it as follows: In the MR model, the demand for products in the retail channel is $D_r = ma - n_1p_r + n_2p_d$; the product demand for online direct sales channels is $D_d = (1-m)a - n_1p_d + n_2p_r$. In the RS model, the demand for products in the retail channel is $D_r = ma - n_1p_r + n_2p_d + \theta_r s_r$; the product demand for online direct sales channels is $D_d = (1-m)a - n_1p_d + n_2p_r + \theta_d s_r$. In the MS model, the demand for products in the retail channel is $D_r = ma - n_1p_r + n_2p_d + \theta_r s_r$; the product demand for online direct sales channels is $D_d = (1-m)a - n_1p_d + n_2p_r + \theta_d s_r$.

TABLE 1. Summary table of parameters.

Notation	Explanation
Parameters	
a	The basic demand for online and offline sales channels, namely the total market demand for products with zero price and no after-sales service, $a > 0$
E_0	The basic recycling amount of online and offline recycling channels, that is, the supply of waste products with a recycling price of zero and no recycling service, depends on the environmental awareness of consumers, and the quantity, $E_0 > 0$
m	The market share of the offline sales channel, $0 < m < 1$, then the basic demand of the offline retail channel is $a_r = ma$, and the basic demand of the online direct sales channel is $a_d = (1-m)a$
k	The quality factor for recycling waste products, $0 < k < 1$, the higher the value, the better the quality of recycled waste products and the lower the cost of remanufacturing
n_1	The elasticity coefficient of product market demand on the product price of its own channel, $n_1 > 0$
n_2	The elasticity coefficient of product market demand on the product price of competitive channels, $n_1 > n_2 > 0$
θ_d	The elasticity coefficient of product market demand on the service level of the direct sales channel, $\theta_d > 0$
θ_r	The elasticity coefficient of product market demand on the service level of the retail channel, $\theta_r > \theta_d > 0$
α_1	The elasticity coefficient of product recycling volume to the recycling price, $\alpha_1 > 0$
α_2	The elasticity coefficient of product recycling volume to the recycling service level, $\alpha_2 > 0$
λ	The proportion of manufacturer's share of retailer's forward service and reverse service input costs, $0 < \lambda < 1$
c_m	Unit manufacturing cost of new products, then the cost of remanufactured products is $(1-k)c_m$, and the cost savings of remanufacturing units is kc_m
$C_r(s_r)$	The cost of after-sales services cost in the forward channel $C_r(s_r) = \frac{\eta_r s_r^2}{2}$, Among them, η_r is the service cost coefficient, $\eta_r > 0$
$C_b(s_b)$	The cost of recycling services in the reverse channel $C_b(s_b) = \frac{\eta_b s_b^2}{2}$, Among them, η_b is the service cost coefficient, $\eta_b > 0$
w	The offline wholesale price paid by the retailer to the manufacturer, which is an exogenous variable, $w > c_m$
Decision variables	
p_d	The direct selling prices of products on the direct sales channel which is determined by the manufacturer
p_r	The retail price of the product in the offline retail channel, which is determined by the retailer
b_1	The highest unit waste product transfer price that the manufacturer is willing to payThe unit transfer price paid by the manufacturer to the retailer is kb_1
b_2	The highest unit recycling price the retailer is willing to payThe unit recycling price paid by retailers to consumers is kb_2
s_r	The level of after-sales service provided by the retailer to consumers
s_b	The level of recycling services provided by the retailer to consumers
Objective function	
Π_d	The manufacturer's revenue, including online sales revenue and offline wholesale revenue
Π_r	The retailer's revenue, including offline sales revenue and offline recycling revenue

3.3.2. Collection volume function

In the closed-loop supply chain system, the recycling party can increase the recycling of waste products by providing certain recycling services, including on-site pickup and other services, so this article considers that the retailer responsible for recycling has a certain level of investment in recycling services. Drawing on

Huang *et al.* [18]'s regulations on recycling volume, the supply function of waste products in the reverse channel is defined as follows: In the MR model, the supply function of waste products is $E(b_2) = E_0 + \alpha_1 k b_2$. In the RS model, the supply function of waste products is $E(b_2) = E_0 + \alpha_1 k b_2 + \alpha_2 \sqrt{\frac{\eta_b}{2}} s_b$. In the MS model, the supply function of waste products is $E(b_2) = E_0 + \alpha_1 k b_2 + \alpha_2 \sqrt{\frac{\eta_b}{2}} s_b$.

4. Model solution and analysis

Under decentralized decision-making, this paper studies the Stackelberg game led by manufacturers. In this case, the manufacturer is in a dominant position in the closed-loop supply chain system, making the decision first, and the retailer making the corresponding decision based on the manufacturer's actions.

4.1. Model MR-No service

In MR model, the game sequence is as follows: The manufacturer first decides the direct selling price of the product p_d and the highest unit waste product transfer price that is willing to pay b_1. After the manufacturer completes the decision, the retailer sets the retail price of the product p_r, and the highest unit recycling price of waste products that is willing to pay b_2. we can get:

$$\begin{aligned} \max \Pi_d^{MR} &= (p_d - c_m) D_d + (W - c_m) D_r + k(c_m - b_1) E(b_2) \\ \text{s.t.} \max \Pi_r^{MR} &= (p_r - W) D_r + k(b_1 - b_2) E(b_2). \end{aligned}$$

Proposition 4.1. *The retailer's profit function Π_r^{MR} is a joint concave function about the retail price p_r and the highest recovery price b_2. The manufacturer's profit function Π_d^{MR} is a joint concave function about the direct selling price p_d and the highest unit waste product transfer price b_1.*

Proposition 4.1 shows that the manufacturer's optimal decision can be derived by first-order derivation of the manufacturer's profit function Π_d^{MR},The retailer's optimal decision can be derived by first-order derivation of the profit function Π_r^R.

According to Proposition 4.1, the optimal decisions of the manufacturer and the retailer under the decentralized decision model are as follows:

Corollary 4.2. *The optimal decisions of the manufacturer are:*

$$\begin{cases} p_d^{MR^*} = \frac{2an_1 - 2amn_1 + 2c_m n_1{}^2 + amn_2 + 2wn_1n_2 - c_m n_1 n_2 - c_m n_2{}^2}{2(2n_1{}^2 - n_2{}^2)} \\ b_1^{MR^*} = \frac{-E_0 + kc_m\alpha_1}{2k\alpha_1} \end{cases}$$

Corollary 4.3. *The optimal decisions of the retailer are:*

$$\begin{cases} p_r^{MR^*} = \frac{4wn_1^3 - n_1n_2(2a(-1+m) + c_m n_2) - n_2^2(am + c_m n_2) + 2n_1^2(2am + c_m \mathrm{n}_2)}{8n_1^3 - 4n_1n_2^2} \\ b_2^{MR^*} = \frac{1}{4}\left(c_m - \frac{3E_0}{k\alpha_1}\right). \end{cases}$$

Proposition 4.4. *Under the MR model, $\partial b_1^{MR^*}/\partial\alpha_1 > 0$, $\partial b_2^{MR^*}/\partial\alpha_1 > 0$.*

Proposition 4.4 shows that when the service is not provided, the price of recycling of used products and the price of transfer payments increase along with the increase of the sensitivity coefficient of the recycling price, that is, when the more sensitive consumers are to the recycling price of used products, the more the companies responsible for recycling have to pay attention to the price level decision.

4.2. Model RS-The retailer undertakes the after-sale service and the recycling service

In RS model, the game sequence is as follows: The manufacturer first decides the direct selling price of the product p_d and the highest unit waste product transfer price that is willing to pay b_1. After the manufacturer completes the decision, the retailer sets the retail price of the product p_r, the service level of the retail channel s_r, the service level of the recycling channel s_b, and the highest unit recycling price of waste products that is willing to pay b_2. we can get:

$$\begin{gathered}\max \Pi_d^{RS} = (p_d - c_m) D_d + (W - c_m) D_r + k (c_m - b_1) E(b_2) \\ \text{s.t. } \max \Pi_r^{RS} = (p_r - W) D_r + k (b_1 - b_2) E(b_2) - \frac{\left(\eta_r {s_r}^2 + \eta_b {s_b}^2\right)}{2}.\end{gathered}$$

Proposition 4.5. *The retailer's profit function Π_r^{RS} is a joint concave function about the retail price p_r and the highest recovery price b_2, and also a joint concave function about the service level of the forward channel s_r and the service level of the reverse channel s_b. It is impossible to judge that the profit function Π_r^R is the joint concave function of retail price p_r, service level of the forward channel s_r, service level of the reverse channel s_b and the highest recovery price b_2. The manufacturer's profit function Π_d^{RS} is a joint concave function about the direct selling price p_d and the highest unit waste product transfer price b_1.*

Proposition 4.5 shows that the manufacturer's optimal decision can be derived by first-order derivation of the manufacturer's profit function Π_d^{RS}, The retailer's optimal decision cannot be derived by first-order derivation of the profit function Π_r^R, but for any given forward channel service level s_r and reverse channel service level s_b, the profit function Π_r^R is related to the only optimal solution for the retail price p_r and the highest recovery price b_2. Therefore, through the two-stage solution method, firstly, the optimal decision of Π_r^{RS} is given for the given s_r and s_b, and then the optimal decision is obtained in the manufacturer's profit formula Π_d^R. Then we get the optimal solutions of s_r and s_b that maximize the profit function Π_r^R, and finally derive the optimal decision of the manufacturer and retailer.

According to Proposition 4.4, the optimal decisions of the manufacturer and the retailer under the decentralized decision model are as follows:

Corollary 4.6. *The optimal decisions of the manufacturer are:*

$$\begin{cases} p_d^{RS^*} = \frac{2an_1 - 2amn_1 + 2c_m {n_1}^2 + amn_2 + 2wn_1n_2 - c_m n_1 n_2 - c_m {n_2}^2 + 2n_1 s_r^{RS^*} \theta_d + n_2 s_r^{RS^*} \theta_r}{2\left(2n_1^2 - {n_2}^2\right)} \\ b_1^{RS^*} = \frac{-2E_0 + 2kc_m\alpha_1 - \sqrt{2} s_b^{RS^*} \alpha_2 \sqrt{\eta_b}}{4k\alpha_1} \end{cases}$$

Corollary 4.7. *The optimal decisions of the retailer are:*

$$\begin{cases} p_r^{RS^*} = \frac{4{w_1}^3 + n_1 n_2\left(-c_m n_2 + 2\left(a - am + s_r^{RS^*}\theta_d\right)\right) - {n_2}^2\left(am + c_m n_2 + s_r^{RS^*}\theta_r\right) + 2{n_1}^2\left(2am + c_m n_2 + 2s_r^{RS^*}\theta_r\right)}{8{n_1}^3 - 4n_1{n_2}^2} \\ b_2^{RS^*} = -\frac{6E_0 - 2kc_m\alpha_1 + 3\sqrt{2} s_b^{RS^*}\alpha_2\sqrt{\eta_b}}{8k\alpha_1} \\ s_r^{RS^*} = -\frac{\left(4wn_1^3 + {n_2}^2(am + c_m n_2) - 2{n_1}^2(2am + c_m n_2) + n_1 n_2(2a(-1+m) + (-4w + c_m)n_2)\right)\left(2n_1 n_2 \theta_d + 4{n_1}^2\theta_r - {n_2}^2\theta_r\right)}{32{n_1}^5\eta_r - 16{n_1}^4{\theta_r}^2 - {n_2}^4{\theta_r}^2 + 4n_1{n_2}^3(2n_2\eta_r + \theta_d\theta_r) - 16{n_1}^3 n_2(2n_2\eta_r + \theta_d\theta_r) - 4{n_1}^2{n_2}^2({\theta_d}^2 - 2{\theta_r}^2)} \\ s_b^{RS^*} = \frac{-\sqrt{2}(E_0 + kc_m\alpha_1)\alpha_2}{(-16\alpha_1 + {\alpha_2}^2)\sqrt{\eta_b}}. \end{cases}$$

Proposition 4.8. *When the condition $16\alpha_1 > \alpha_2^2$ is satisfied, $b_1^{MR^*} > b_1^{MR^*}$, $b_2^{MR^*} > b_2^{MR^*}$.*

Proposition 4.8 shows that when the recovery price sensitivity coefficient and recovery service sensitivity coefficient meet certain conditions, the recovery price and transfer payment price under the condition of providing recovery service are lower than those without providing recovery service. Enterprises providing recycling services should pay attention to consumers' recycling needs in a timely manner, make reasonable recycling plans, and win consumers' satisfaction in both price and service.

4.3. Model MS-The manufacturer undertakes the after-sale service, and the retailer undertakes the recycling service

In MS model, the game sequence is as follows: The manufacturer first decides the direct selling price of the product p_d, the service level of the retail channel s_r and the highest unit waste product transfer price that is willing to pay b_1. After the manufacturer completes the decision, the retailer sets the retail price of the product p_r, the service level of the recycling channel s_b and the highest unit recycling price of waste products that is willing to pay b_2. we can get:

$$\max \Pi_d^{MS} = (p_d - c_m) D_d + (W - c_m) D_r + k(c_m - b_1)E(b_2) - \frac{\eta_r s_r^2}{2}$$
$$\text{s.t. } \max \Pi_r^{MS} = (p_r - W) D_r + k(b_1 - b_2)E(b_2) - \frac{\eta_b s_b^2}{2}.$$

Proposition 4.9. *The retailer's profit function Π_r^{MS} is a joint concave function about the retail price p_r and the highest recovery price b_2. It is impossible to judge that the profit function Π_r^{MS} is the joint concave function of retail price p_r, service level of the reverse channel s_b and the highest recovery price b_2. The manufacturer's profit function Π_d^{MS} is a joint concave function about the direct selling price p_d and the highest unit waste product transfer price b_1. It is impossible to judge that the profit function Π_d^{MS} is the joint concave function of the direct selling price p_d, the highest unit waste product transfer price b_1 and service level of the forward channel s_r.*

Proposition 4.9 shows that the manufacturer's optimal decision cannot be derived by first-order derivation of the manufacturer's profit function Π_d^{MS}, and the retailer's optimal decision cannot be derived by first-order derivation of the profit function Π_r^{MS}, but for any given reverse channel service level s_b, the profit function Π_r^{MS} is related to the only optimal solution for the retail price p_r and the highest recovery price b_2, and for any given forward channel service level s_r, the profit function Π_d^{MS} is related to only optimal solution for the direct selling price p_d, the highest unit waste product transfer price b_1. Therefore, through the two-stage solution method, firstly, the optimal decision of Π_r^{MS} is given for the given s_b, and then the optimal decision Π_d^{MS} is obtained in the manufacturer's profit formula by the given s_r. Then we get the optimal solutions of s_b and s_r that maximize the profit function Π_r^{MS} and Π_d^{MS}, and finally derive the optimal decision of the manufacturer and retailer.

According to Proposition 4.5, the optimal decisions of the manufacturer and the retailer under the decentralized decision model are as follows:

Corollary 4.10. *The optimal decisions of the manufacturer are:*

$$\begin{cases} p_j^{MS^*} = \frac{2an_1 - 2am_1n_1 + 2c_m n_1^2 + amn_2 + 2wn_1n_2 - c_m n_1 n_2 - c_m n_2^2 + 2n_1 s_r^{MS^*}\theta_d + n_2 s_r^{MS^*}\theta_r}{2(2n_1^2 - n_2^2)} \\ b_1^{MS^*} = \frac{-2E_0 + 2kc_m\alpha_1 - \sqrt{2}s_b^{MS^*}\alpha_2\sqrt{\eta_b}}{4k\alpha_1} \\ s_r^{MS^*} = \frac{n_z^2(am + c_m n_2)\theta_r - 2n_1^2((2a(-1+m) + (-2w + c_m)n_2)\theta_d) + c_m n_2\theta_r) + n_1n_2(2am + 2c_m n_2)\theta_d + (2a(-1+m) + c_n n_2)\theta_r) - 4n_1^3(-w\theta_r + c_m(\theta_d + \theta_r))}{8n_1^3\eta_r - 4n_1^2\theta_d^2 - n_2^2\theta_r^2 - 4n_1n_2(n_1\eta_1 + \theta_d\theta_r)}. \end{cases}$$

Corollary 4.11. *The optimal decisions of the retailer are:*

$$\begin{cases} p_r^{MS^*} = \frac{4wn_1^3 + n_1n_2(-c_m n^2 + 2(a - am + s_r^{MS^*}\theta_d)) - n_2^2(am + c_m n_2 + s_r^{MS^*}\theta_r) + 2n_1^2(2am + c_m n_2 + 2s_r^{MS^*}\theta_r)}{8n_1^3 - 4n_1 n_2^2} \\ b_2^{MS^*} = -\frac{6E_0 - 2kc_m\alpha_1 + 3\sqrt{2}s_b^{MS^*}\alpha_2\sqrt{\eta_b}}{8k\alpha_l} \\ s_b^{MS^*} = \frac{-\sqrt{2}E_0\alpha_2 - \sqrt{2}kc_m\alpha_l\alpha_2}{(-16\alpha_1 + \alpha_2^2)\sqrt{\eta_b}}. \end{cases}$$

TABLE 2. Decision-making results.

	Model MR
p_d	$\frac{2a\mathbf{n}_1 - 2am\mathbf{n}_1 + 2c_m\mathbf{n}_1^2 + am\mathbf{n}_2 + 2w\mathbf{n}_1\mathbf{n}_2 - c_m\mathbf{n}_1\mathbf{n}_2 - c_m\mathbf{n}_2^2}{2(2\mathbf{n}_1^2 - \mathbf{n}_2^2)}$
p_r	$\frac{4w{n_1}^3 - n_1n_2(2a(-1+m) + c_mn_2) - {n_2}^2(am + c_mn_2) + 2{n_1}^2(2am + c_mn_2)}{8{n_1}^3 - 4n_1{n_2}^2}$
b_1	$\frac{-E_0 + kc_m\alpha_1}{2k\alpha_1}$
b_2	$\frac{1}{4}\left(c_m - \frac{3E_0}{k\alpha_1}\right)$
s_r	
s_b	
	Model RS
p_d	$\frac{2an_1 - 2amn_1 + 2c_mn_1^2 + amn_2 + 2wn_1n_2 - c_mn_1n_2 - c_mn_2^2 + 2n_1s_r^{RS^*}\theta_d + n_2s_r^{RS^*}\theta_r}{2(2n_1^2 - n_2^2)}$
p_r	$\frac{4w{n_1}^3 + n_1n_2(-c_mn_2 + 2(a - am + s_r^{RS^*}\theta_d)) - {n_2}^2(am + c_mn_2 + s_r^{RS^*}\theta_r) + 2{n_1}^2(2am + c_mn_2 + 2s_r^{RS^*}\theta_r)}{8{n_1}^3 - 4n_1{n_2}^2}$
b_1	$\frac{-2E_0 + 2kc_m\alpha_1 - \sqrt{2}s_b^{RS^*}\alpha_2\sqrt{\eta_b}}{4k\alpha_1}$
b_2	$-\frac{6E_0 - 2kc_m\alpha_1 + 3\sqrt{2}s_b^{RS^*}\alpha_2\sqrt{\eta_b}}{8k\alpha_1}$
s_r	$\frac{(4w{n_1}^3 + {n_2}^2(am + c_mn_2) - 2{n_1}^2(2am + c_mn_2) + n_1n_2(2a(-1+m) + (-4w + c_m)n_2))(2n_1n_2\theta_d + 4{n_1}^2\theta_r - {n_2}^2\theta_r)}{32{n_1}^5\eta_r + 16{n_1}^4\theta_r^2 + {n_2}^4{n_r}^2 - 4n_1{n_2}^3(2n_2\eta_r + \theta_d\theta_r) + 16{n_1}^3n_2(2n_2\eta_r + \theta_d\theta_r) + 4{n_1}^2{n_2}^2(\theta_d^2 - 2\theta_r^2)}$
s_b	$\frac{-\sqrt{2}(E_0 + kc_m\alpha_1)\alpha_2}{(-16\alpha_1 + \alpha_2^2)\sqrt{\eta_b}}$
	Model MS
p_d	$\frac{2an_1 - 2amn_1 + 2c_mn_1^2 + amn_2 + 2wn_1n_2 - c_mn_1n_2 - c_mn_2^2 + 2n_1s_r^{MS^*}\theta_d + n_2s_r^{MS^*}\theta_r}{2(2n_1^2 - n_2^2)}$
p_r	$\frac{4w{n_1}^3 + n_1n_2(-c_mn_2 + 2(a - am + s_r^{MS^*}\theta_d)) - {n_2}^2(am + c_mn_2 + s_r^{MS^*}\theta_r) + 2{n_1}^2(2am + c_mn_2 + 2s_r^{MS^*}\theta_r)}{8{n_1}^3 - 4n_1{n_2}^2}$
b_1	$\frac{-2E_0 + 2kc_m\alpha_1 - \sqrt{2}s_b^{MS^*}\alpha_2\sqrt{\eta_b}}{4k\alpha_1}$
b_2	$-\frac{6E_0 - 2kc_m\alpha_1 + 3\sqrt{2}s_b^{MS^*}\alpha_2\sqrt{\eta_b}}{8k\alpha_1}$
s_r	$\frac{{n_2}^2(am + c_mn_2)\theta_r - 2{n_1}^2((2a(-1+m) + (-2w + c_m)n_2)\theta_d + c_mn_2\theta_r) + n_1n_2(2(am + c_mn_2)\theta_d + (2a(-1+m) + c_mn_2)\theta_r) - 4{n_1}^3(-w\theta_r + c_m(\theta_d + \theta_r))}{8{n_1}^3\eta_r - 4{n_1}^2\theta_d^2 - {n_2}^2\theta_r^2 - 4n_1n_2(n_2\eta_r + \theta_d\theta_r)}$
s_b	$\frac{-\sqrt{2}E_0\alpha_2 - \sqrt{2}kc_m\alpha_1\alpha_2}{(-16\alpha_1 + {\alpha_2}^2)\sqrt{\eta_b}}$

5. COMPARISIONS AMONG DIFFERENT MODELS

Table 2 summarizes decision-making results of each supply chain member under the three service strategy models. This part carries out numerical analysis to explore the impact of services on the decision-making and revenue of supply chain members, and some valuable conclusions can be obtained. After investigation and analysis, electronic products and office equipment account for a large proportion in the second-hand recycling market [35]. This section takes HP's printing equipment as an example, and sets the relevant parameters.

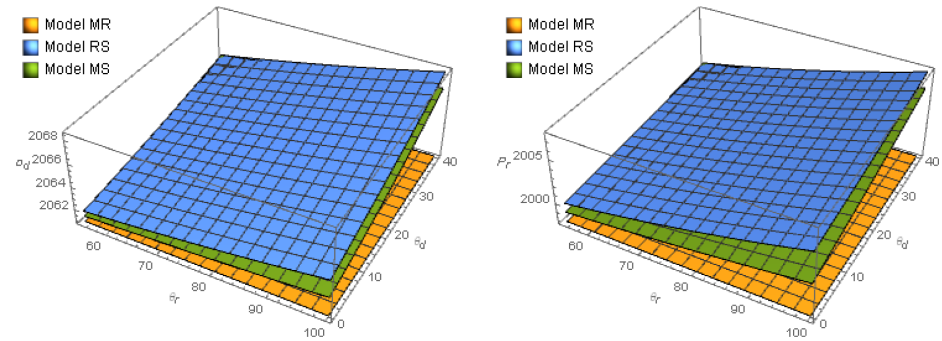
5.1. The impact of θ_r and θ_d

This part mainly analyzes the influence of consumers' sensitivity coefficient to forward service on the optimal decision-making of the manufacturer and the retailer. During the analysis of the example, values of parameters are shown in Table 3. Set the value range of θ_r to [55,100] and the value range of θ_d to [0,40].

In the three service strategy models, the best direct selling price is $P_d^{RS} > P_d^{MS} > P_d^{MR}$, and the best retail price is $P_r^{RS} > P_r^{MS} > P_r^{MR}$. Figure 2 shows that the direct sales price and retail price of products under

TABLE 3. Value of parameters in the numerical study.

Parameters	a	m	w	n_1	n_2	c_m	E_0	k	α_1	α_2	η_b	η_r
Value	20000	0.5	1200	8	6	1000	100	0.6	18	4	100000	100000



(a) (b)

FIGURE 2. The impact of θ_r and θ_d on the direct selling price. (a) The impact of θ_r and θ_d on the direct selling price. (b) The impact of θ_r and θ_d on the retail price.

the RS model are the highest, followed by the MS model and the MR model the lowest. This is because the provision of product after-sales service has increased the total value of the product, and the direct sales price and retail price of the product will increase as the total value of the product increases. From Figure 2, it can also be obtained that when the level of after-sales service investment is not zero, no matter what service provision mode is, the direct sales price and retail price increase with the increase of consumers' sensitivity to services. Under the RS model, when consumers have a certain demand for product after-sales service, the retailer will invest more cost in product service, so the retailer will increase the price of the product to ensure its own profit, and in this case, the manufacturer is beneficiary, not only do not need to bear the responsibility of providing services, but there is also the phenomenon of "service free-riding". In order to encourage retailers to provide after-sales services, the manufacturer takes the measure of increasing direct selling prices.

In the two service strategy models, the best after-sales service level is $s_r^{RS} > s_r^{MS}$. It can be seen from Figure 3 that the after-sales service level of products under the RS model is higher than the after-sales service level of the products under the MS model, and with the increase of consumers' sensitivity to services, the service level of the positive channel shows an increasing trend. As the undertaker of offline product sales, the retailer has more direct and close contact with consumers, which makes them also show certain advantages in providing offline services. When the retailer finds that consumers are more sensitive to services, it will promptly improve the after-sales service level of their products to improve consumer satisfaction.

In the three service strategy models, the best profits of the manufacturer is $\pi_d^{MS} > \pi_d^{RS} > \pi_d^{MR}$, the best profits of the retailer is $\pi_r^{MS} > \pi_r^{RS} > \pi_r^{MR}$. It can be seen from Figure 4 that the profits of the manufacturer and the retailer are the highest under the MS model, followed by the RS model, and the MR model the lowest. Combining Figures 2 and 3, it can be seen that although the direct sales price, retail price and after-sales service level of products under the RS model are higher than those under the MS model. However, compared with model MS, model RS has a negative impact on the market demand for products in terms of after-sales service provision, which in turn leads to the highest profits for manufacturers and retailers under model MS. From the perspective of ensuring corporate profits and after-sales service levels, it is more appropriate for the manufacturer to provide after-sales service and the retailer to provide recycling services.

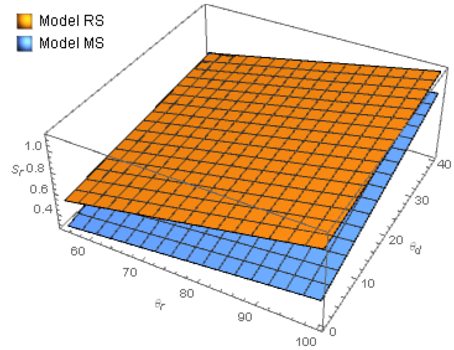


FIGURE 3. The impact of θ_r and θ_d on the forward service level.

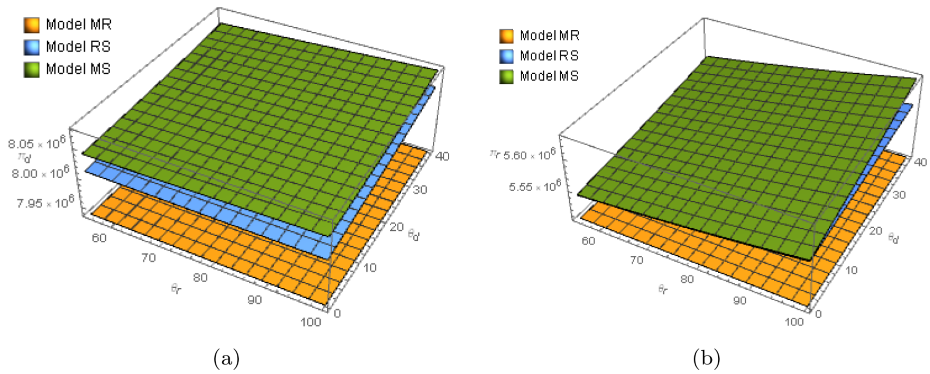


FIGURE 4. The impact of θ_r and θ_d on the profits of the manufacturer and the retailer. (a) The impact of θ_r and θ_d on the the profits of the manufacturer. (b) The impact of θ_r and θ_d on the profits of the retailer.

TABLE 4. Value of parameters in the numerical study.

Parameters	a	m	w	n_1	n_2	c_m	θ_r	θ_d	E_0	k	α_1	η_b	η_r
Value	20000	0.5	1200	8	6	1000	60	30	100	0.6	18	100000	100000

5.2. The impact of α_2

This part mainly analyzes the influence of consumers' sensitivity coefficient to reverse service on the optimal decision-making of the manufacturer and the retailer. Since the discussion of recycling services in this article only includes non-recycling services and retailers providing recycling services, Model RS and Model MS have the same optimal decisions in reverse channels. Therefore, when discussing the optimal decision-making of recovery price, transfer payment price and recovery service level, this paper uses Model RS as an example, which does not affect the final analysis result. During the analysis of the example, values of parameters are shown in Table 4, and the value range of α_2 is set as.

In the two service strategy models, the best transfer price is $b_1^{MR} > b_1^{RS} = b_1^{MS}$, the best recovery price is $b_2^{MR} > b_2^{RS}$ (Prop. 4.8), the best quantity of waste products recovered is $E(b_2^{RS})=E(b_2^{MS})>E(b_2^{MR})$. It can be seen from Figures 5, 6 and 7, that compared with model MR, the transfer payment price and recycling price

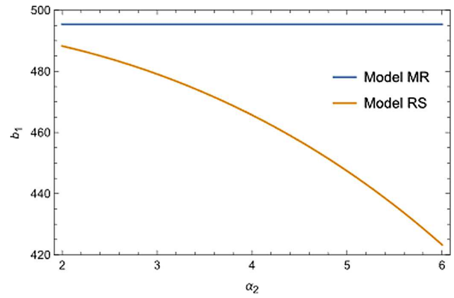


FIGURE 5. The impact of α_2 on the transfer price.

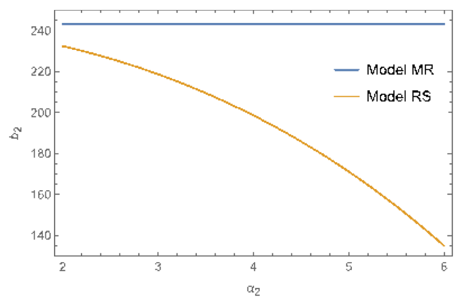


FIGURE 6. The impact of α_2 on the recovery price.

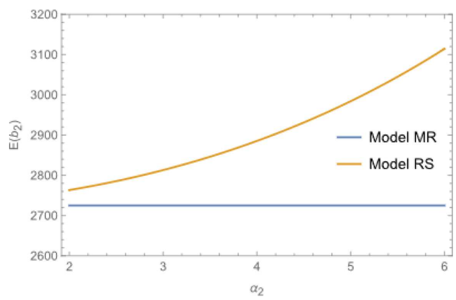


FIGURE 7. The impact of α_2 on the quantity of waste products recovered.

under model RS (model MS) are lower, and the recycling volume of waste products is higher. At the same time, under model RS (model MS), as the sensitivity of the recycling service increases, the transfer payment price and recycling price will gradually decrease, and the recycling volume of waste products will gradually increase, and the changes will become more and more significant. In the recycling stage of waste products, the retailer providing recycling services will incur a certain service cost, so it will adopt a method of reducing recycling prices, and accordingly the manufacturer will also respond by reducing the transfer payment price. Compared with the situation where no recycling service is provided, Model RS (Model MS) increases the amount of recycling of waste products. From the perspective of sustainable development, the retailer provides recycling services to better realize resource recycling.

In the three service strategy models, the best profit of the manufacturer is $\pi_d^{MS} > \pi_d^{RS} > \pi_d^{MR}$, the best profit of the retailer is $\pi_r^{MS} > \pi_r^{RS} > \pi_r^{MR}$. From Figure 8, it can be seen that the profits of the manufacturer

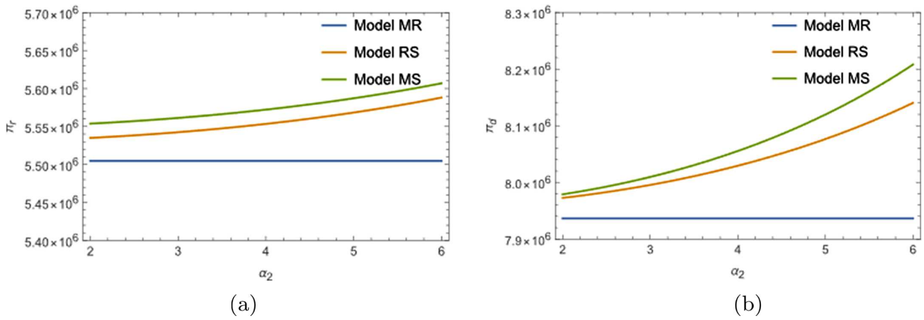


FIGURE 8. The impact of α_2 on the profits of the manufacturer and the retailer. (a) The impact of α_2 on the profits of the manufacturer. (b) The impact of α_2 on the profits of the retailer.

and the retailer are the highest under the MS model, followed by the model, and the MR model is the lowest. Under the MS and RS models, the profits of the manufacturer and the retailer increase with the increase in the sensitivity of recycling services. In the case of the retailer providing recycling services, the transfer payment price and recycling prices have fallen, and the recycling volume of waste products has increased. Therefore, both the manufacturer and the retailer benefit from the mode of providing recycling services. Combined with the existing conclusions, the model of the manufacturer providing after-sales service and the retailer providing recycling services can have a positive effect on the profits of enterprises, and it also promotes the development of circular economy under the closed-loop supply chain and better realizes the concept of sustainable development. For members on the dual-channel closed-loop supply chain, this is the best service strategy choice.

6. Supply chain coordination mechanism

After systematic comparison, we found that the manufacturer provides after-sales service and the retailer provides recycling service. The service strategy is the best choice for members of the DCCLSC. However, due to the decentralized structure, both the manufacturer and the retailer make decisions based on their own benefit maximization, the total system profit and supply chain performance can also reach a better level through coordination contracts. In view of the fact that the service provision strategy analyzed in this article is real, the study of supply chain coordination in this part is meaningful. In this section, based on the model that the manufacturer provides the after-sales service and the retailer provide recycling service, we design a service cooperation contract that shares service costs to achieve Pareto improvements and better performance. The service contract is set as (X,Y), where X represents the proportion of the cost incurred by the manufacturer to provide the after-sales service to the retailer, and Y represents the proportion of the cost incurred by the retailer to provide the recycling service borne by the manufacturer. We aim to provide a better and more efficient supply chain coordination structure for companies that implement DCCLSC management and focus on services.

6.1. Service cost-sharing mechanism

In this section, we consider the coordination relationship between the manufacturer and the retailer for service cost sharing, and build a Stackelberg game model (referred to as C-MS) to analyze whether this service contract can effectively coordinate the closed-loop supply chain. And how this service will promote the profit of the supply chain and the decision-making of each member of the supply chain. Therefore, the game sequence is as follows in C-MS model: The manufacturer first decides the direct selling price of the product p_d, the service level of the retail channel s_r and the highest unit waste product transfer price that is willing to pay b_1. After the manufacturer completes the decision, the retailer sets the retail price of the product p_r, the service level of

TABLE 5. Value of parameters in the numerical study.

Parameters	a	m	w	n_1	n_2	c_m	θ_r	θ_d	E_0	k	α_1	α_2	η_b	η_r
Value	20000	0.5	1200	8	6	1000	60	30	100	0.6	18	4	100000	100000

the recycling channel s_b and the highest unit recycling price of waste products that is willing to pay b_2. we can get:

$$\max \Pi_d^{C-MS} = (\mathbf{p}_d - \mathbf{c}_m)\,\mathbf{D}_d + (\mathbf{W} - \mathbf{c}_m)\,\mathbf{D}_r + k(\mathbf{c}_m - \mathbf{b}_1)\mathbf{E}(\mathbf{b}_2) - \frac{(1-\mathbf{X})\eta_r s_r^2}{2} - \frac{\mathbf{Y}\eta_b s_b^2}{2}$$
$$\text{s.t.}\max \prod_r^{C-MS} = (\mathrm{p}_r - \mathrm{W})\mathrm{D}_r + k(\mathrm{b}_1 - \mathrm{b}_2)\mathrm{E}(\mathbf{b}_2) - \frac{\mathrm{X}\eta_r s_r^2}{2} - \frac{(1-\mathrm{Y})\eta_b s_b^2}{2}$$

Similar to the solving process of the model MS, the optimal decisions of the manufacturer and the retailer under the decentralized decision model are as follows:

Corollary 6.1. *The optimal decisions of the manufacturer are:*

$$\begin{cases} \rho_d^{C-MS^*} = \frac{2an_1-2amn_1+2c_m n_1^2+amn_2+2wn_1n_2-c_m n_2^2+2n_1 s_r^{MS^*}\theta_d+n_2 s_r^{MS^*}\theta_r}{2(2n_1^2-n_2^2)} \\ b_1^{C-MS^*} = \frac{-2E_0+2kc_m\alpha_1-\sqrt{2}s_b^{MS^*}\alpha_2\sqrt{\eta_b})}{4k\alpha_l} \\ s_r^{C-MS^*} = \frac{-n_2^2(am+c_n n_2)\theta_r+2n_1^2((2a(-1+m)+(-2W+c_m)n_2)\theta_d+c_m n_2\theta_r)-n_1n_2(2(am+c_n n_2)\theta_d+(2a(-1+m)+c_m n_2)\theta_r)+4n_1^3(-W\theta_r+c_m(\theta_d+\theta_r))}{8(-1+8X)n_1^3\eta_r+4n_1^2\theta_d^2+n_2^2\theta_r^2+4n_1n_1(-(-1+X)n_2\eta_r+\theta_d\theta_r} \end{cases}.$$

Corollary 6.2. *The optimal decisions of the retailer are:*

$$\begin{cases} p_r^{C-MS^*} = \frac{4wn_1^3+n_1n_2(-c_m n_2+2(a-am+s_r^{C-MS^*}\theta_d))-n_2^2(am+c_m n_2+s_r^{C-MS^*}\theta_r)+2n_1^2(2am+c_m n_2+2s_r^{C-MS^*}\theta_r)}{8n_1^3-4n_1n_2^2} \\ b_2^{C-MS^*} = -\frac{6E_0-2kc_m\alpha_1+3\sqrt{2}s_h^{C-MS^*}\alpha_2\sqrt{\eta_b}}{8k\alpha_1} \\ s_h^{C-MS^*} = \frac{-\sqrt{2}E_0\alpha_2-\sqrt{2}kc_m\alpha_1\alpha_2}{(-16(1-Y)\alpha_1+\alpha_2^2)\sqrt{\eta_b}} \end{cases}.$$

6.2. The impact of(X,Y)

According to the optimal decision-making of supply chain members under the obtained service contract, this section adopts the method of calculation example analysis to mainly analyze the impact of our proposed service cooperation contract (X,Y) on the profit of the manufacturer and the retailer and the total profits of the supply chain. In the process of example analysis, the value of parameters is shown in Table 5. Set the value range of X to [0, 0.8] and the value range of Y to [0, 0.6]. The final numerical analysis result is shown in the figure below.

As shown in Figures 9, 10 and 11, at a certain cost ratio, the profits of the manufacturer and the retailer and the system profit are greater than the system profit without cost sharing, which shows that the service cooperation contract of the manufacturer and the retailer has a positive impact on the profits of the manufacturer and the retailer and the system profit. The performance of the closed-loop supply chain system and the efficiency of the supply chain have been improved, which can achieve the Pareto improvement of the DCCLSC system under cost sharing. For the manufacturer implementing DCCLSC management, when faced with a service provision strategy, it should actively develop service cooperation with retailers, and give full play to the advantages of the service model of "manufacturers provide after-sales service and retailers provide recycling services". On the one hand, the manufacturer can achieve a "win-win" situation and Pareto improvement of the supply chain system. On the other hand, it also can encourage consumers to invest in the recycling of waste products, promote the formation of a circular economy, and further realize the concept of sustainable development of social environmental protection.

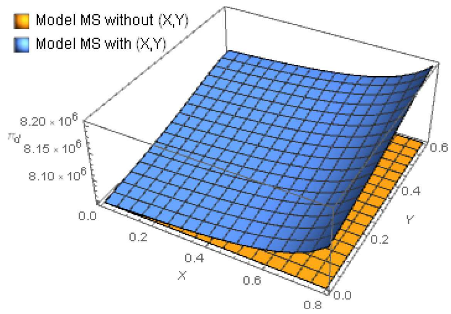


FIGURE 9. The impact of (X,Y) on the profits of the manufacturer.

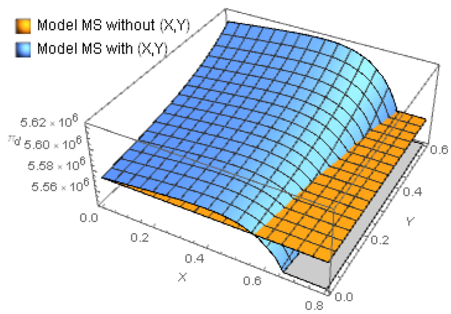


FIGURE 10. The impact of (X,Y) on the profits of the retailer.

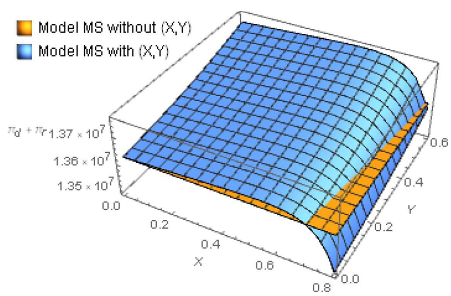


FIGURE 11. The impact of (X,Y) on the profits of the retailer.

7. Conclusion

With the continuous development of internet technology and the increasing awareness of consumers' environmental protection, the dual-channel closed-loop supply chain management that combines online direct sales channels and retail channels has received more and more attention. However, the existing research has ignored the service research of the dual-channel closed-loop supply chain, so this article mainly studies the role of service in the dual-channel closed-loop supply chain, and analyzes the performance of the supply chain under different service strategy structures, and this article focuses on how to give full play to the role of the service area. In the research process, we constructed three service strategy models (MR model, RS model, MS model), compared and analyzed the optimal decision of each model, and proposed a service cooperation mechanism to achieve Pareto improvement of the supply chain system. The research found that: (1) After-sales service and recycling services play a positive role in the dual-channel closed-loop supply chain. On the one hand, companies can increase their own profits by adjusting service levels. On the other hand, enterprises can also encourage consumers to actively participate in recycling activities by improving service levels, forming a corporate circular economy, and enhancing the corporate social responsibility and influence; (2) It is better for the manufacturer to provide after-sales service and the retailer to provide recycling services. Compared with the after-sales service provided by the retailer, the after-sales service provided by the manufacturer can bring more benefits; (3) The service cooperation mechanism introduced under the MS model can increase the profit of each member of the supply chain and the profit of the system, and this improves the efficiency of the supply chain to a certain extent and realizes the Pareto improvement of the supply chain system.

For companies implementing dual-channel closed-loop supply chain management, they can pay more attention to service strategies in the management process. In the case of comprehensive consideration of corporate resources, the manufacturer can actively interact with retailers, seek service cooperation, do a good job in the division of after-sales service and recycling services, and set up a reasonable service cost sharing mechanism to achieve "win-win" cooperation. In this way, companies can better realize the concept of environmental protection for sustainable development and enhance their social benefits.

Appendix A.

The proof of Proposition 4.1:

First, for retailers, solving the second-order partial derivatives of the retailer profit function Π_r with respect to p_r and b_2, we can get the second-order Hessian matrix as follows:

$$\begin{bmatrix} -2n_1 & 0 \\ 0 & -2k^2\alpha_1. \end{bmatrix}$$

The analysis shows that the first-order determinant of the obtained fourth-order Hessian matrix is $-2n_1 < 0$, the second-order principal sub-formula is $4n_1k^2\alpha_1 > 0$. Therefore, the retailer's profit function is about the joint concave function of p_r and b_2. The first-order derivation of p_r and b_2 can be combined to solve the optimal solution of p_r and b_2.

Then, the second-order partial derivatives of the manufacturer's profit function about p_d and b_1 are solved, and the second-order Hessian matrix is obtained as follows:

$$\begin{bmatrix} -2n_1 + \frac{n_2^2}{n_1} & 0 \\ 0 & -k^2\alpha_1. \end{bmatrix}$$

The analysis shows that the first-order determinant of the obtained second-order Hessian matrix is $-2n_1 + \frac{n_2^2}{n_1} < 0$, the second-order principal sub-formula is $-(-2n_1 + \frac{n_2^2}{n_1})k^2\alpha_1 > 0$, Therefore, the manufacturer's profit function Π_d is about the joint concave function of p_d and b_1. The first-order derivation of p_d and b_1 can be combined to solve the optimal solution of p_d and b_1.

Specific steps are as follows:

(1) Find the optimal solution of p_r and b_2.
For the retailer profit function, the optimal solution for p_r and b_2 is obtained. The results are as follows:
$p_r^{MR^*} = \frac{ma + wn_1 + n_2p_d}{2n_1}$
$b_2^{MR^*} = \frac{-E_0 + kb_1\alpha_1}{2k\alpha_1}$.

(2) Bring $p_r^{MR^*}$ and $b_2^{MR^*}$ into the retailer's profit function Π_r, and by solving the first-order derivative results of p_d and b_1 simultaneously, the optimal solution of p_d and b_1 is obtained:
$p_d^{MR^*} = \frac{2an_1 - 2amn_1 + 2c_mn_1^2 + amn_2 + 2wn_1n_2 - c_mn_1n_2 - c_mn_2^2}{2(2n_1^2 - n_2^2)}$

$b_1^{MR^*} = \frac{-E_0+kc_m\alpha_1}{2k\alpha_1}$.

(3) Bring the obtained optimal solutions of s_r and s_b into $p_r^{MR^*}$ and $b_2^{MR^*}$, and to obtain the optimal solutions of p_r and b_2.

$p_r^{MR^*} = \frac{4wn_1^3-n_1n_2(2\alpha(-1+m)+c_mn_2)-n_2^2(am+c_mn_2)+2n_1^2(2\alpha m+c_mn_2)}{8n_1^3-4n_1n_2^2}$

$b_2^{MR^*} = \frac{1}{4}(c_m - \frac{3E_0}{k\alpha_1})$.

The proof of Proposition 4.4:

$\partial b_1^{MR^*}/\partial\alpha_1 = \frac{\mathrm{e}_0}{2k\alpha_1^2} > 0, \partial {b_2}^{MR^*}/\partial\alpha_1 = \frac{3\mathrm{e}_0}{4k\alpha_1^2} > 0.$

The proof of Proposition 4.5:

First, for retailers, solving the second-order partial derivatives of the retailer profit function with respect to p_r, b_2, s_r and s_b, we can get the fourth-order Hessian matrix as follows:

$$\begin{bmatrix} -2n_1 & 0 & \theta_r & 0 \\ 0 & -2k^2\alpha_1 & 0 & -\frac{k\alpha_2\sqrt{\eta_b}}{\sqrt{2}} \\ theta_r & 0 & -\eta_r & 0 \\ 0 & -\frac{k\alpha_2\sqrt{\eta_b}}{\sqrt{2}} & 0 & -\eta_b \end{bmatrix}.$$

The analysis shows that the first-order determinant of the obtained fourth-order Hessian matrix is $-2n_1 < 0$, the second-order principal sub-formula is $4n_1k^2\alpha_1 > 0$, the third-order principal sub-formula $-2k^2\alpha_1(2n_1\eta_r - \theta_r^2)$ and the fourth-order principal sub-formula $\frac{1}{2}k^2(4\alpha_1 - \alpha_2^2)\eta_b(2\,\mathrm{n}_1\,\eta_r - \theta_r^2)$ cannot determine positive or negative. Therefore, the retailer's profit function is about the joint concave function of p_r and b_2, not the joint concave function of p_r, b_2, s_r and s_b.

In addition, by solving the second-order partial derivatives of the retailer's profit function Π_r with respect to s_r and s_b, the second-order Hessian matrix is obtained as follows:

$$\begin{bmatrix} -\eta_r & 0 \\ 0 & -\eta_b \end{bmatrix}.$$

The analysis shows that the first-order determinant of the obtained second-order Hessian matrix is $-\eta_r < 0$, the second-order principal sub-formula is $\eta_r\eta_b > 0$. Therefore, the retailer profit function Π_r is about the joint concave function of s_r and s_b.

In summary, in the decentralized decision-making mode, a two-stage optimization method can be adopted. First, we assume that s_r and s_b are known, and solve the optimal solutions of p_d, p_r, b_1 and b_2, then derive the optimal solutions of s_r and s_b that maximize the retailer's profit. Finally, s_r and s_b are brought into the expressions of p_d, p_r, b_1 and b_2 to find the optimal solutions of p_d, p_r, b_1 and b_2. Specific steps are as follows:

(1) Given s_r and s_b, find the optimal solution of p_d, p_r, b_1 and b_2.
First, for the retailer profit function, the optimal solution for p_r and b_2 is obtained. The results are as follows:

$p_r^{RS^*}(s_r, s_b) = \frac{ma+wn_1+n_2p_d+s_r\theta_r}{2n_1}$
$b_2^{RS^*}(s_r, s_b) = \frac{-2E_0+2kb_1\alpha_1-\sqrt{2}s_b\alpha_2\sqrt{\eta_b}}{4k\alpha_1}$.

Then, the obtained optimal solutions of p_r and b_2 are brought into the manufacturer's profit function, and the second-order partial derivatives of the manufacturer's profit function Π_d about p_d and b_1 are solved, and the second-order Hessian matrix is obtained as follows:

$$\begin{bmatrix} -2n_1 + \frac{n_2^2}{n_1} & 0 \\ 0 & -k^2\alpha_1 \end{bmatrix}.$$

The analysis shows that the first-order determinant of the obtained second-order Hessian matrix is $-2n_1 + \frac{n_2^2}{n_1} < 0$, the second-order principal sub-formula is $-(-2n_1 + \frac{n_2^2}{n_1})k^2\alpha_1 > 0$, Therefore, the manufacturer's profit function Π_d is about the joint concave function of p_d and b_1. The first-order derivation of p_d and b_1 can be combined to solve the optimal solution of p_d and b_1. The results are as follows:

$$p_d^{RS^*}(s_r, s_b) = \frac{2an_1 - 2amn_1 + 2c_m {n_1}^2 + amn_2 + 2wn_1n_2 - c_m n_1 n_2 - c_m n_2^2 + 2n_1 s_r \theta_d + n_2 s_r \theta_r}{2(2n_1^2 - n_2^2)}$$

$$b_1^{RS^*}(s_r, s_b) = \frac{-2E_0 + 2kc_m\alpha_1 - \sqrt{2}s_b\alpha_2\sqrt{\eta_b}}{4k\alpha_1}$$

$$p_r^{RS^*}(s_r, s_b) = \frac{4wn_1^3 + n_1n_2(-c_m n_2 + 2(a - am + s_r\theta_d)) - n_2^2(am + c_m n_2 + s_r\theta_r) + 2n_1^2(2am + c_m n_2 + 2s_r\theta_r)}{8n_1^3 - 4n_1n_2^2}$$

$$b_2^{RS^*}(s_r, s_b) = -\frac{6E_0 - 2kc_m\alpha_1 + 3\sqrt{2}s_b\alpha_2\sqrt{\eta_b}}{8k\alpha_1}.$$

(2) Bring $p_d^{d^*}(s_r, s_b)$, $b_1^{d^*}(s_r, s_b)$, $p_r^{d^*}(s_r, s_b)$ and $b_2^{d^*}(s_r, s_b)$ into the retailer's profit function Π_r, and by solving the first-order derivative results of s_r and s_b simultaneously, the optimal solution of s_r and s_b is obtained:

$$s_r^{RS*} = -\frac{(4wn_1^3 + {n_2}^2(am + c_m n_2) - 2{n_1}^2(2am + c_m n_2) + n_1n_2(2a(-1+m) + (-4w + c_m)n_2))(2n_1n_2\theta_d + 4{n_1}^2\theta_r - {n_2}^2\theta_r)}{32{n_1}^5\eta_r - 16{n_1}^4\theta_r^2 - {n_2}^4\theta_r^2 + 4n_1{n_2}^3(2n_2\eta_r + \theta_d\theta_r) - 16{n_1}^3 n_2(2n_2\eta_r + \theta_d\theta_r) - 4{n_1}^2{n_2}^2(\theta_d^2 - 2\theta_r^2)}$$

$$s_b^{RS^*} = \frac{-\sqrt{2}(E_0 + kc_m\alpha_1)\alpha_2}{(-16\alpha_1 + \alpha_2^2)\sqrt{\eta_b}}.$$

(3) Bring the obtained optimal solutions of $p_d^{d^*}(s_r, s_b)$, $b_1^{d^*}(s_r, s_b)$, $p_r^{d^*}(s_r, s_b)$ and $b_2^{d^*}(s_r, s_b)$, and to obtain the optimal solutions of p_d, p_r, b_1 and b_2.

$$p_d^{RS^*} = \frac{2an_1 - 2amn_1 + 2c_m n_1^2 + amn_2 + 2wn_1n_2 - c_m n_1n_2 - c_m n_2^2 + 2n_1 s_r^{RS^*}\theta_d + n_2 s_r^{RS^*}\theta_r}{2(2n_1^2 - n_2^2)}$$

$$b_1^{RS^*} = \frac{-2E_0 + 2kc_m\alpha_1 - \sqrt{2}s_b^{RS^*}\alpha_2\sqrt{\eta_b}}{4k\alpha_1}$$

$$p_r^{RS^*} = \frac{4wn_1^3 + n_1n_2(-c_m n_2 + 2(a - am + s_r^{RS^*}\theta_{d'})) - n_2^2(am + c_m n_2 + s_r^{RS^*}\theta_r) + 2n_1^2(2am + c_m n_2 + 2s_r^{RS^*}\theta_r)}{8n_1^3 - 4n_1n_2^2}$$

$$b_2^{RS^*} = -\frac{6E_0 - 2kc_m\alpha_1 + 3\sqrt{2}s_b^{RS^*}\alpha_2\sqrt{\eta_b}}{8k\alpha_1}.$$

The proof of Proposition 4.8:

When the condition $16\alpha_1 > {\alpha_2}^2$ is satisfied, ${b_1}^{MR^*} - {b_1}^{RS^*} = \frac{(\mathrm{e}_0 + kc_m\alpha_1)\alpha_2^2}{2k\alpha_1(16\alpha_1 - \alpha_2^2)} > 0$, ${b_2}^{MR^*} - {b_2}^{RS^*} = \frac{3(\mathrm{e}_0 + kc_m\alpha_1)\alpha_2^2}{4k\alpha_1(16\alpha_1 - \alpha_2^2)} > 0$.

The proof of Proposition 4.9: First, for retailers, solving the second-order partial derivatives of the retailer profit function Π_r with respect to p_r, b_2 and s_b, we can get the fourth-order Hessian matrix as follows:

$$\begin{bmatrix} -2n_1 & 0 & 0 \\ 0 & -2k^2\alpha_1 & -\frac{k\alpha_2\sqrt{\eta_b}}{\sqrt{2}} \\ 0 & -\frac{k\alpha_2\sqrt{\eta_b}}{\sqrt{2}} & -\eta_b \end{bmatrix}.$$

The analysis shows that the first-order determinant of the obtained third-order Hessian matrix is $-2n_1 < 0$, the second-order principal sub-formula is $4n_1k^2\alpha_1 > 0$, the third-order principal sub-formula $k^2 n_1(-4\alpha_1 + {\alpha_2}^2)\eta_b$ cannot determine positive or negative. Therefore, the retailer's profit function is about the joint concave function of p_r and b_2, not the joint concave function of p_r, b_2 and s_b.

In summary, in the decentralized decision-making mode, a two-stage optimization method can be adopted. First, we assume that s_b is known, and solve the optimal solutions of p_d, b_1, p_r, b_2 and s_r, then derive the optimal solutions of s_b that maximize the retailer's profit Π_r. Finally, s_b is brought into the expressions of p_d, b_1, p_r, b_2 and s_r to find the optimal solutions of p_d, b_1, p_r, b_2 and s_r. Specific steps are as follows:

(1) Given s_b, find the optimal solution of p_d, b_1, p_r, b_2 and s_r.
First, for the retailer profit function, the optimal solution for p_r and b_2 is obtained. The results are as follows:

$$p_r^{MS^*}(s_r, s_b) = \frac{ma+wn_1+n_2p_d+s_r\theta_r}{2n_1}$$
$$b_2^{MS^*}(s_r, s_b) = \frac{-2E_0+2kb_1\alpha_1-\sqrt{2}s_b\alpha_2\sqrt{\eta_b}}{4k\alpha_1}.$$

Then, the obtained optimal solutions of p_r and b_2 are brought into the manufacturer's profit function, and the third-order partial derivatives of the manufacturer's profit function Π_d about p_d, b_1 and s_r are solved, and third -order Hessian matrix is obtained as follows:

$$\begin{bmatrix} -2n_1+\frac{n_2^2}{n_1} & 0 & \theta_d+\frac{n_2\theta_r}{2n_1} \\ 0 & -k^2\alpha_1 & 0 \\ \theta_d+\frac{n_2\theta_r}{2n_1} & 0 & -\eta_r \end{bmatrix}.$$

The analysis shows that the first-order determinant of the obtained second-order Hessian matrix is $-2n_1+\frac{n_2^2}{n_1}<0$, the second-order principal sub-formula is $-(-2n_1+\frac{n_2^2}{n_1})k^2\alpha_1>0$, the third-order principal subformula $\frac{-k^2\alpha_1^2(8{n_1}^3\eta_r-4{n_1}^2\theta_d^2-{n_2}^2\theta_r^2-4n_1n_2(n_2\eta_r+\theta_d\theta_r)}{{n_1}^2(4\alpha_1-{\alpha_2}^2)}$ cannot determine positive or negative Therefore, the manufacturer's profit function Π_d is about the joint concave function of p_d and b_1, not the joint concave function of p_d, b_1 and s_r. We assume that s_r is known, and solve the optimal solutions of p_d and b_1. The first-order derivation of p_d and b_1 can be combined to solve the optimal solution of p_d and b_1. The results are as follows:

$$p_d^{MS^*}(s_r, s_b) = \frac{2an_1-2amn_1+2c_mn_1^2+amn_2+2wn_1n_2-c_mn_1n_2-c_mn_2^2+2n_1s_r\theta_d+n_2s_r\theta_r}{2(2n_1^2-n_2^2)}$$
$$b_1^{MS^*}(s_r, s_b) = \frac{-2E_0+2kc_m\alpha_1-\sqrt{2}s_b\alpha_2\sqrt{\eta_b}}{4k\alpha_1}$$
$$p_r^{MS^*}(s_r, s_b) = \frac{4wn_1^3+n_1n_2(-c_mn_2+2(a-am+s_r\theta_s))-n_2^2(am+c_mn_2+s_r\theta_r)+2n_1^2(2am+c_mn_2+2s_r\theta_r)}{8n_1^3-4n_1n_2^2}$$
$$b_2^{MS^*}(s_r, s_b) = -\frac{6E_0-2kc_m\alpha_1+3\sqrt{2}s_b\alpha_2\sqrt{\eta_b}}{8k\alpha_1}.$$

(2) Bring $p_d^{MS^*}(s_r, s_b)$, $b_1^{MS^*}(s_r, s_b)$, $p_r^{MS^*}(s_r, s_b)$ and $b_2^{MS^*}(s_r, s_b)$ into the retailer's profit function Π_r, and by solving the first-order derivative results of s_r and s_b simultaneously, the optimal solution of and is obtained:

$$s_r^{MS^*} = \frac{{n_2}^2(am+c_mn_2)\theta_r-2{n_1}^2((2a(-1+m)+(-2W+c_m)n_2)\theta_d+c_mn_2\theta_r)+n_1n_2(2(am+c_mn_2)\theta_d+(2n(-1+m)+c_mn_2)\theta_r)-4n_1^3(-W\theta_r+c_m(\theta_d+\theta_r))}{8{n_1}^3\eta_r-4{n_1}^2\theta_d^2-{n_2}^2\theta_r^2-4n_1n_2(\mathfrak{n}_2\eta_r+\theta_d\theta_r)}$$
$$s_b^{MS^*} = \frac{-\sqrt{2}(E_0+kc_m\alpha_1)\alpha_2}{(-16\alpha_1+\alpha_2^2)\sqrt{\eta_b}}.$$

(3) Bring the obtained optimal solutions of $p_d^{d^*}(s_r, s_b)$, $b_1^{d^*}(s_r, s_b)$, $p_r^{d^*}(s_r, s_b)$ and $b_2^{d^*}(s_r, s_b)$, and to obtain the optimal solutions of p_d, b_1, p_r and b_2.

$$p_d^{MS^*} = \frac{2an_1-2amn_1+2c_mn_1^2+amn_2+2wn_1n_2-c_mn_1n_2-c_mn_2^2+2n_1s_r^{MS^*}\theta_d+n_2s_r^{MS^*}\theta_r}{2(2n_1^2-n_2^2)}$$
$$b_1^{MS^*} = \frac{-2E_0+2kc_m\alpha_1-\sqrt{2}s_b^{MS^*}\alpha_2\sqrt{\eta_b}}{4k\alpha_1}$$
$$p_r^{MS^*} = \frac{4wn_1^3+n_1n_2(-c_mn_2+2(a-am+s_r^{MS^*}\theta_{d'}))-n_2^2(am+c_mn_2+s_r^{MS^*}\theta_r)+2n_1^2(2am+c_mn_2+2s_r^{MS^*}\theta_r)}{8n_1^3-4n_1n_2^2}$$
$$b_2^{MS^*} = -\frac{6E_0-2kc_m\alpha_1+3\sqrt{2}s_b^{MS^*}\alpha_2\sqrt{\eta_b}}{8k\alpha_1}.$$

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