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Optimizing Operating Parameters of a Dual E-Commerce-Retail Sales Channel in a Closed-Loop Supply Chain

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ABSTRACT Currently, many consumers prefer online shopping via e-commerce platforms because of the shopping convenience and product diversity. Meanwhile, offline retailers provide retail services to cope with the competition from e-commerce platforms. Additionally, environment protection has been regarded to be equally important as economic growth in meeting the challenges of sustainable development goals. This work uses consumer utility selection theory to form the online and offline market demand functions in a dual-channel closed-loop supply chain considering consumers' e-commerce preferences and retail services. Then, we further reveal the optimal system sales channel and coordination contract to acquire good economic and ecological benefits. We find the following: 1) As in practice, consumers' e-commerce preferences and retail services simultaneously affect the purchasing and sales channels. 2) Since both consumers' e-commerce preferences and retail service quality increase as service costs decreases, the recovery rate of used products increases, which contributes to improving the ecological benefits. 3) The ''Double Marginalization'' problem can reduce the operating efficiency of the decentralized system. Accordingly, we design a revenue-service cost sharing contract to solve this problem in a coordinated manner, and thus increase the economic and ecological benefits of the system. Consequently, all members can obtain profits in a win-win scenario by bargaining on the revenue rates and service costs.

INDEX TERMS Channel strategy, coordination, e-commerce preferences, closed-loop supply chain, retail services.

I. INTRODUCTION

Currently, the sales volume of e-commerce platforms is sharply increasing. In 2019, global consumers' online shopping expenditures reached \$3.551 trillion, which accounted for 12.4% of the global total sales (Global Ecommerce 2019, Andrew Lipsman) [1]. The Destination Management Organizations (DMO) estimates that US online sales will exceed \$740 billion by 2024 (Retail e-commerce sales in the United States from 2017 to 2024) [2]. China's National Bureau of Statistics reported that China's online marketing sales reached \$577.7 billion in the first three quarters of 2019. Manufacturers can well meet consumers' e-commerce preferences and promote products sales by adopting an online sales channel. Therefore, increasingly more manufactures operate dual-channel strategies with online and traditional offline sales channels. However, e-commerce platforms have tremendous effects on brick and mortar stores. Many retailers face the dilemma that they cannot make ends meet and must close due to consumers' e-commerce shopping behavior [3], [4]. To cope with the sales competition from the online sales channel and maintain market demand, retailers can provide services to customers to increase offline shopping utility [5]. These services include shopping guides and consultations, free trials, free promotional materials, and merchandise displays to improve consumers' positive attitudes [6]–[9]. In addition, the online and offline interaction in a dual-channel supply chain allows consumers to buy products online and pick them up in the store (BOPS), and BOPS has become a popular choice among consumers' shopping behaviors [10], [11]. As a result, consumers' e-commerce preferences must trade-off the offline on-site experience and online convenience, which affects manufacturers' sales channel (offline, online and dual-channel) strategies.

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In recent years, resource shortages and environmental pollution problems have become increasingly more serious. The rapid developments of e-commerce technology inevitably accelerate product upgrades to promote products and this thus greatly shortens a product's life cycle, which in turn causes excessive consumption of ecological resources and an increased amount of waste materials [12]. To realize sustainable development and follow of 3R1D (Reduce, Reuse, Recycle and Degradable) principles, we need to solve the recycling and reuse problems of waste and discarded products [13]–[15]. In recent years, closed-loop supply chain management has attracted a great deal of concern from academia and industry. It mainly considers the recycling and remanufacturing activities of waste and discarded products [16]–[18] and can achieve the goals of resource reuse and environment protection. In practice, companies such as Foxconn, IBM, and Haier have successfully acquired good economic and ecological benefits by remanufacturing their products [19]–[21]. Therefore, it is of practical significance to explore different social capital and behaviors [22].

Driven by the above reasons, we want to answer the following questions: 1) What are the conditions in which a manufacturer starts an e-commerce platform after considering the impacts of consumer preferences and retail services? 2) How do consumer and retailer behaviors affect the economic and ecological benefits of a dual-channel closed-loop supply chain? 3) Are the economic and ecological benefits in a centralized system better than those in a decentralized system? 4) Can a revenue-service cost sharing contract solve the "Double Marginalization" problem in a decentralized dual-channel closed-loop supply chain in a coordinated manner, and further allow all members to achieve win-win results and good economic and ecological benefits?

The existing studies have the following characteristics: 1) The studies of the traditional dual-channel supply chain considering consumers' e-commerce preferences and retail services only pay attention to economic benefits. 2) The studies of the dual-channel closed-loop supply chain only use Bertrand's theory to depict the competition between the online and offline sales channels and few of them consider that retailers can provide retails service to cope with e-commerce sales [15]. Although these studies intuitively reflect the competitive relationship between the online and offline sales channels using Bertrand's theory, they cannot fundamentally analyze how consumers' e-commerce preferences and retail services affect all members' decision-making in a dual-channel closed-loop supply chain and the economic and ecological benefits of the closed-loop system. To overcome these shortcomings and answer the above questions, we quantify the market demand with consumer utility selection theory in a dual-channel closed-loop supply chain, and use game theory and the backward induction method to analyzes all members' decision-making behaviors.

The main contributions and innovations of this paper are as follows:

1) We determine the market demand in a dual-channel closed-loop supply chain considering consumers' e-commerce preferences and retail services using consumer utility selection theory. This paper is the first to consider the impacts of both consumers' e-commerce preference sand retail services in a closed-loop supply chain. 2) We extend the existing literature on dual-channel supply chain management by capturing the feature of channel strategies. This feature, through which channel strategies are affected by consumers' e-commerce preferences and retail services, is rarely mentioned in previous studies. We also determine the optimal decisions in different channel strategies and provide the managerial insights on the parameters of consumers' e-commerce preferences and retail services. 3) In spite of the obvious phenomenon in practice that opening a direct online channel can alleviate the "Double Marginalization" problem, we analytically find that, to some extent, a retailer's self-interested behavior leads to a certain markup in selling products and transferring recycled products to manufacturers, and this makes the economic and ecological benefits in a decentralized system lower than those in a centralized system. 4) Different from the previous studies on dual-channel supply chains that focus on revenue or cost sharing contracts, we design a revenue-service cost sharing contract to solve the "Double Marginalization" problem in a coordinated manner and improve the economic and ecological benefits of the dual-channel closed-loop system.

The remainder of this paper is organized as follows: Section II introduces the current status and gaps in the research. In Section III, we describe the problem and determine the market demand functions in a dual-channel closed-loop supply chain system. In Section IV, the manufacturer's sales channel strategy is analyzed, and the impacts of e-commerce preferences and retail services on system decision-making are also determined. We design a revenue-service cost sharing contract to improve the operating efficiency to obtain better economic and ecological benefits in Section V. Section VI verifies the results of this paper with numerical examples. Section VII gives the conclusions and managerial insights.

II. LITERATURE REVIEW

This work mainly involves dual-channel competition, retail services in a supply chain and a dual-channel closed-loop supply chain. In this section, we summarize the existing studies from these three aspects, respectively.

A. DUAL-CHANNEL COMPETITION

In the past, some scholars have focused on competition between online and offline sales channels. Chiang *et al.* [23] and Shi *et al.* [12] used the consumer utility selection theory to quantify competing market demands in a dual-channel system. Chiang *et al.* [23] found that the introduction of a direct online channel can alleviate the "Double Marginalization" problem and increase the manufacturer's profits. Shi *et al.* [12] discussed the optimal channel choice strategy in a dual-channel system. In addition, Zhou *et al.* [24], Yan *et al.* [25], Chen *et al.* [26] and Zhang *et al.* [27] used Bertrand's theory to quantitatively assess competing market demands in online and offline sales channels. Zhou *et al.* [24] investigated how consumers' e-commerce preferences affect a manufacturer's sales channel choice in a low-carbon dual-channel supply chain. Yan *et al.* [25] found that the financing behaviors of retailers can help them to adjust their bargaining power and weak the competing impact of the direct online channel. Chen *et al.* [26] recognized that opening a direct online channel can improve product quality and system operating efficiency. Zhang *et al.* [27] constructed a decision model for a retailer's leadership. They found that consumers' e-commerce preferences can affect a retailer's sales channel choice. He *et al.* [28] considered the influence of the price and delivery lead time on channel choice. They concluded that the introduction of a dual-channel model can alleviate the "Double Marginalization" problem and improve all members' profits.

Although the introduction of an online channel can alleviate the "Double Marginalization" problem [23], [28], the self-interested behavior of retailers inevitably makes the offline retail channel have certain markups. For this reason, Cai *et al.* [29] designed a price discount contract to solve the problem in a dual-channel supply chain in a coordinated manner. Chen *et al.* [30] used profit-sharing contracts so that all members achieve win-win profits in a dual-channel supply chain.

From the above discussion, we can clearly find that there are two methods of quantifying the competing market demands of the online and offline sales channels in a traditional supply chain. One is the consumer utility selection theory, and the other is Bertrand's theory. Different from the existing literatures that focus on the traditional supply chain, we research the channel competition problem for a dual-channel closed-loop supply chain and take into account the economic and ecological benefits. To fundamentally analyze the impact of consumers' e-commerce preferences and retail services on the closed-loop system, we use consumer utility selection theory to quantify the competing market demands of online and offline sales channels. We also research how to solve the "Double Marginalization" problem in the dual-channel closed-loop supply chain with contracts.

B. RETAIL SERVICES IN A SUPPLY CHAIN

In practice, many retailers adopt retail services to cope with the competition from e-commerce platforms. Hence, some scholars have studied a dual-channel supply chain system in which a retailer provides retail services to attract consumers to buy products in the offline retail channel. Yan *et al.* [31] and Zhang *et al.* [32] used consumer utility selection theory to measure the market demand of the online and offline sales channels when retail services exist. Yan *et al.* [31] analyzed the strategic role of retail services in a dual-channel supply chain. They pointed out that retail services can effectively alleviate channel conflict and achieve win-win results for manufacturers and retailers. Zhang *et al.* [32] indicated that when the investment efficiency of retail services is very high and the retailer holds a large downward estimated deviation for the manufacturer's direct sales costs, retail services can alleviate the impact of the online sales channel and improve system performance.

Different from the above achievements, Dan *et al.* [33] and Zhou *et al.* [24] employed Bertrand's theory to characterize the competing market demands in online and offline sales channels, and built a dual-channel supply chain model where retail services exist. Dan *et al.* [33] found that retail services have a significant impact on manufacturers' and retailers' decision-making. Zhou *et al.* [24] considered the free-riding behavior of the direct online channel on retail services. They showed that the free-riding behavior influences retailers' service strategy and all members' profits. In addition, sales effort is a useful strategy for retail services in a supply chain. Chen *et al.* [34] studied the impact of sales effort on demand, and Cai *et al.* [4] pointed out that sales effort can ease the pressure of channel competition. Therefore, the above studies show that in different channel systems, the behavior of retailers has an important influence on channel decision-making.

In this paper, we study a dual-channel closed-loop supply chain to determine how retail services are used to cope with e-commerce competition and influence manufacturers' channel choices and analyze how to achieve good economic and ecological benefits. Our research can fill the research gap related to retail services in dual-channel closed-loop supply chain management.

C. DUAL-CHANNEL CLOSED-LOOP SUPPLY CHAIN

To acquire good economic and ecological benefits, some scholars focus on dual-channel closed-loop supply chain management [35]–[37]. Using Bertrand's theory to quantify the market demand in a dual-channel closed-loop system, Ma *et al.* [38] found that government consumption subsidies can increase market demand and are beneficial to all members. He *et al.* [39] considered a dual-channel closed-loop supply chain with government subsidies in which the manufacturer opens a direct online channel to sell remanufactured products and entrusts the retailer to sell new products. Their study showed that government subsidies can increase the recovery rate of used products. Gan *et al.* [40] indicated that a dual-channel strategy can increase the system profits compared with the single-channel strategy. They also concluded that consumers' acceptance of remanufactured products and e-commerce preferences affect all members' profits. The "Double Marginalization" problem inevitably exists in a dual-channel closed-loop system. Xie *et al.* [41] designed a revenue sharing contract, and Zheng *et al.* [42] designed a two–part tariff contract to solve the problem.

Different from the above research on a using a dual-channel closed-loop supply chain to quantify the market demands of the online and offline sales channels with Bertrand's theory, we use consumer utility selection theory

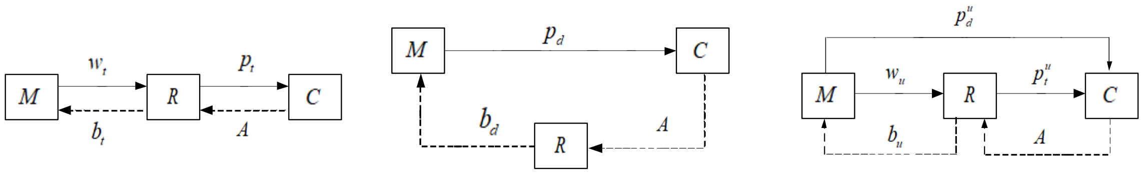

FIGURE 1. Closed-loop supply chain operations chart. (a). Offline retail channel. (b). Direct online channel. (c). Dual-channels.

to analyze the competitive relationship between e-commerce platforms and retail stores. In addition, we design a revenue-service cost sharing contract to solve the "Double Marginalization" problem in the dual-channel closed-loop supply chain and improve the economic and ecological benefits of the closed-loop system.

III. PROBLEM DESCRIPTION

In a dual-channel closed-loop supply chain system composed of a manufacturer and a retailer, both the manufacturer and retailer have a Stackelberg game relationship. The manufacturer is the leader, and has power to operate three kinds of sales channels: offline retail, direct online and dual-channels with online and offline sales channels. The manufacturer entrusts the following retailer to recycle used products for complete remanufacturing, and the new and remanufactured products are homogeneous. The same as literatures [38] and [43], we assume that the recycling of used products is uneconomical, and the recovery cost is $C = C_L\tau^2$ for the recovery rate of used products τ $(0 \le \tau \le 1)$. The parameter C_L defined in the recovery cost function is assumed to be large enough, such that $0 \le \tau \le 1$ [19]. To ensure the profitability of the remanufacturing of used products, we assume that the unit production cost of the remanufactured products is less than that of a new product, i.e., $c_r < c_n$. The operating process of the dual-channel closed-loop supply chain is shown in Figure 1(c). On this basis, the case where the manufacturer only opens an offline retail channel or a direct online channel are shown in Figure 1(a) and Figure 1(b), respectively. In Figure 1, full lines represent new product retail channel, and the dashed lines represent used product recycling channel.

We assume that consumers are heterogeneous in their valuations of the product and make their decisions on their purchasing channels by maximizing their utility. We denote the utility evaluation of a product (alternatively called "consumer's willingness to pay") as v, and it is uniformly distributed in the range of [0, 1]. The consumer utility obtained from the product in the offline retail channel is assumed to be v $(0 \le v \le 1)$, and that in the direct online channel is assumed to be θv [23], where θ represents consumers' e-commerce preferences. $0 < \theta < 1$ means that the utility of the same product bought from the online channel is lower than that bought from the offline channel due to the lack of personal experience and instant access.

To cope with the competition from the online sales channel [31], [32], the retailer can provide retail services to consumers. We assume that the service level is s $(0 < s < 1)$. Then, the degree of promotion of retail services for demand is λs, and the corresponding service costs are $C(s) = \frac{\beta s^2}{2}$. λ $(0 < \lambda < 1)$ is the sensitivity of the service quality to the service level, and β $(0 < \beta \le 1)$ is the sensitivity of the service costs to the service level.

We assume that consumers purchase products from the online channel at price p_d^u (unit direct sales price) and from the offline channel at price p_t^u(unit retail sales price). The consumer surpluses of the product when bought from the online and offline channels are U_d and U_t, respectively. Accordingly, a consumer with utility evaluation v will derive a consumer surplus of $U_d = \theta v - p_d^u$ when buying the product from the online channel, and a consumer surplus of $U_t = v - p_t^u + \lambda s$ when buying the product from the offline channel [23]. When a consumer obtains the same surplus from buying products from the online and offline channels $U_d = U_t$ and $\theta v - p_d = v - p_t + \lambda s$. The indifference point for consumer buying products from the online and offline channels is $v_u = \frac{p_t^u - \lambda s - p_d^u}{1-\theta}$. Then, the consumer chooses the offline retail channel to buy the product only if his utility evaluation is not less than $v_u = \frac{p_t^u - \lambda s - p_d^u}{1-\theta}$, or chooses the direct online channel only if his utility evaluation is less than $v_u = \frac{p_t^u - \lambda s - p_d^u}{1-\theta}$. Note that consumers would purchase products only when they have positive utility. Thus, we have $0 < \lambda s < p_t < 1$.

We assume that the potential scale of the market demand is 1 [24]. Based on the above indifference point and comparing the different utility levels of consumers [26], the following situations are obtained:

Case 1: If $v_t > v_d$, then $v_u > v_t > v_d$. 1) If $v_u < 1$, from Figure 2(1a), we can find that the market demand in the offline retail channel is $Q_t^u = \int_{v_u}^1 1\,dv = 1 - \frac{p_t^u - \lambda s - p_d^u}{1-\theta}$, and the market demand in the direct online channel is $Q_d^u = \int_{v_d}^{v_u} 1\,dv = \frac{p_t^u - \lambda s - p_d^u}{1-\theta} - \frac{p_d^u}{\theta}$. 2) If $v_u > 1$, from Figure 2(1b), we can find that the market demand in the offline retail channel is $Q_t^u = 0$, and the market demand in the direct online channel is $Q_d^u = \int_{v_d}^1 1\,dv = 1 - \frac{p_d^u}{\theta}$.

Case 2: If $v_t < v_d$, then $v_u < v_t < v_d$. From Figure 2(2), we can find that the market demand in the offline retail channel is $Q_t^u = \int_{v_t}^1 1\,dv = 1 - p_t^u + \lambda s$, and the market demand in the direct online channel is $Q_d^u = 0$.

Table 1 summarizes the notations used in this paper.

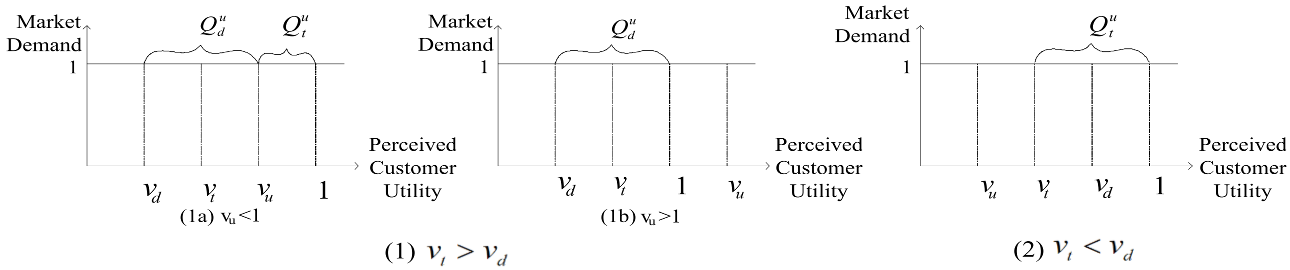

FIGURE 2. The market demand in a dual-channel closed-loop supply chain.

TABLE 1. Notations definitions.

Symbols	Explanation
c_n	Unit production cost of new products.
c_r	Unit remanufactured cost of recycled products.
Δ	Unit cost savings of producing recycled products compared with the new ones, where $\Delta = c_n - c_r$.
A	Unit recovery price for the retailer that recycles used products from the consumer.
b	Unit recovery price for the manufacturer that recycles used products from the retailer, where $A \le b \le \Delta$.
C_L	Coefficient of recovery cost.
τ	Recovery rate of used products.
w	Unit wholesale price for the manufacturer that sells products to the retailer.
p	Unit sales price of the product.
v	Utility evaluation of the product.
θ	Consumers' e-commerce preferences.
s	Retail service level.
λ	Sensitivity of the service quality to the service level.
β	Sensitivity of the service costs to the service level.
Q	Market demand.
U	Consumer surplus.
Π	Member's profits.

Note: The subscript "t" indicates the endogenous variable corresponding to the offline retail channel. The subscript "d" indicates the endogenous variable corresponding to the direct online channel. The subscript and superscript "u" indicate the endogenous variable corresponding to the dual-channels. The superscript "C" indicates the variable corresponding to the centralized supply chain. The superscript "$*$" indicates the optimal decision result. $\Pi_j^{i*}(i=M,R;j=t,d,u)$ represents the profit of each member $i(i=M,R)$ in the three kinds of sales channels $j(j=t,d,u)$, and $\Pi_j^{C*}(j=t,d,u)$ represents the profits from the three kinds of sales channels $j(j=t,d,u)$ in centralized decision-making [23].

According to Cases 1 and 2, there are three kinds of sales channels: offline retail, direct online and dual-channels with online and offline sales channels. The market demand functions for these channels are as follows:

$$Q_t^u = \begin{cases} 0, & 1-\theta+p_d^u+\lambda s < p_t^u < 1 \\ 1-\dfrac{p_t^u-\lambda s-p_d^u}{1-\theta}, & \dfrac{p_d^u}{\theta}+\lambda s \le p_t^u \le 1-\theta+p_d^u+\lambda s \\ 1-p_t^u+\lambda s, & p_d^u+\lambda s < p_t^u \le \dfrac{p_d^u}{\theta}+\lambda s \end{cases} \tag{1}$$

$$Q_d^u = \begin{cases} 1-\dfrac{p_d^u}{\theta}, & 1-\theta+p_d^u+\lambda s < p_t^u < 1 \\ \dfrac{p_t^u-p_d^u-\lambda s}{1-\theta}-\dfrac{p_d^u}{\theta}, & \dfrac{p_d^u}{\theta}+\lambda s \le p_t^u \le 1-\theta+p_d^u+\lambda s \\ 0, & p_d^u+\lambda s < p_t^u \le \dfrac{p_d^u}{\theta}+\lambda s \end{cases} \tag{2}$$

Based on the above assumptions and market demand functions of the three kinds of sales channels, in the next section, we do the following:

First, we develop profit models of the manufacturer and the retailer in a decentralized closed-loop supply chain. Second, we use Stackelberg game theory and the backward induction method to analyze the optimal pricing, service and recycling decisions. Furthermore, we analyze the sales channel strategy of the closed-loop supply chain. Then, we investigate how the parameters of consumers' e-commerce preferences and retail services affect the operating strategies of the closed-loop supply chain. Finally, we provide a summary for the overview of all corollaries in a decentralized closed-loop supply chain.

IV. OPTIMAL CHANNEL AND DECISION ANALYSIS

In practice, all members are independent decision makers in a supply chain system, and every one of them seeks to maximize their own profits, which is what we call a decentralized system. By analyzing the revenues and costs of all members in the decentralized dual-channel closed-loop supply chain, we can obtain the profit functions of the manufacturer and the retailer as follows:

$$\Pi_u^M\left(w, p_d^u, b\right) = (w-c_n)\,Q_t^u + \left(p_d^u-c_n\right)Q_d^u + (\Delta-b)\,\tau Q^u \tag{3}$$

$$\Pi_u^R\left(p_t^u, \tau, s\right) = \left(p_t^u-w\right)Q_t^u + (b-A)\,\tau Q^u - C_L\tau^2 - \frac{\beta s^2}{2} \tag{4}$$

TABLE 2. Channel selection strategy for the decentralized closed-loop supply chain.

Channel strategy / Optimal results	$0 \le \theta \le \theta_\alpha^R$ Offline retail channel	$\max\{\theta_\alpha^R, 0\} < \theta < \min\{\theta_\beta^R, 1\}$ Dual-channel	$\theta_\beta^R \le \theta \le 1$ Direct online channel
w^*	$\frac{1+c_n}{2}$	$\frac{1+\theta}{2} - \frac{4C_L\theta(\theta-c_n)}{8C_L\theta-(\Delta-A)^2}$	----
b^*	Δ	$\frac{\Delta+A}{2}$	$\frac{\Delta+A}{2}$
p_t^*	$\frac{\beta\left[2C_L-(\Delta-A)^2\right]+C_L(\beta-\lambda^2)(1+c_n)}{2C_L(2\beta-\lambda^2)-\beta(\Delta-A)^2}$	$\frac{1+\theta}{2} - \frac{4C_L\theta(\theta-c_n)}{8C_L\theta-(\Delta-A)^2} + \frac{\beta(1-\theta)^2}{2\left[2\beta(1-\theta)-\lambda^2\right]}$	----
p_d^*	---	$\theta - \frac{4C_L\theta(\theta-c_n)}{8C_L\theta-(\Delta-A)^2}$	$\theta - \frac{4C_L\theta(\theta-c_n)}{8C_L\theta-(\Delta-A)^2}$
Q_t^*	$\frac{\beta C_L(1-c_n)}{2C_L(2\beta-\lambda^2)-\beta(\Delta-A)^2}$	$\frac{\beta(1-\theta)}{2\left[2\beta(1-\theta)-\lambda^2\right]}$	---
Q_d^*	---	$\frac{4C_L(\theta-c_n)}{8C_L\theta-(\Delta-A)^2} - \frac{\beta(1-\theta)}{2\left[2\beta(1-\theta)-\lambda^2\right]}$	$\frac{4C_L(\theta-c_n)}{8C_L\theta-(\Delta-A)^2}$
τ^*	$\frac{\beta(1-c_n)(\Delta-A)}{2\left[2C_L(2\beta-\lambda^2)-\beta(\Delta-A)^2\right]}$	$\frac{(\theta-c_n)(\Delta-A)}{8C_L\theta-(\Delta-A)^2}$	$\frac{(\theta-c_n)(\Delta-A)}{8C_L\theta-(\Delta-A)^2}$
s_d^*	$\frac{\lambda C_L(1-c_n)}{2C_L(2\beta-\lambda^2)-\beta(\Delta-A)^2}$	$\frac{\lambda(1-\theta)}{2\left[2\beta(1-\theta)-\lambda^2\right]}$	0
Π^{M*}	$\frac{\beta C_L(1-c_n)^2}{2\left[2C_L(2\beta-\lambda^2)-\beta(\Delta-A)^2\right]}$	$\frac{2C_L(\theta-c_n)^2}{8C_L\theta-(\Delta-A)^2} + \frac{\beta(1-\theta)^2}{4\left[2\beta(1-\theta)-\lambda^2\right]}$	$\frac{2C_L(\theta-c_n)^2}{8C_L\theta-(\Delta-A)^2}$
Π^{R*}	$\frac{\beta C_L(1-c_n)^2}{4\left[2C_L(2\beta-\lambda^2)-\beta(\Delta-A)^2\right]}$	$\frac{C_L(\Delta-A)^2(\theta-c_n)^2}{\left[8C_L\theta-(\Delta-A)^2\right]^2} + \frac{\beta(1-\theta)^2}{8\left[2\beta(1-\theta)-\lambda^2\right]}$	---
Π^{T*}	---	---	$\frac{C_L(\Delta-A)^2(\theta-c_n)^2}{\left[8C_L\theta-(\Delta-A)^2\right]^2}$

$$\theta_\alpha^R = \frac{\left[8C_L\beta+16C_L\beta c_n-8C_L\lambda^2-\beta(\Delta-A)^2\right]-\sqrt{\left[8C_L\beta+16C_L\beta c_n-8C_L\lambda^2-\beta(\Delta-A)^2\right]^2-32C_L\beta\left[16C_L\beta c_n-8C_L\lambda^2c_n-\beta(\Delta-A)^2\right]}}{16C_L\beta}$$

$$\theta_\beta^R = \frac{\left[8C_L\beta+16C_L\beta c_n-8C_L\lambda^2-\beta(\Delta-A)^2\right]+\sqrt{\left[8C_L\beta+16C_L\beta c_n-8C_L\lambda^2-\beta(\Delta-A)^2\right]^2-32C_L\beta\left[16C_L\beta c_n-8C_L\lambda^2c_n-\beta(\Delta-A)^2\right]}}{16C_L\beta}$$

In the decentralized dual-channel closed-loop supply chain, the leading manufacturer determines the unit recovery price, the unit wholesale price and the unit direct sales price; and the following retailer determines the recovery rate of used products, the unit retail sales price and the retail service level. Considering the Stackelberg game relationship between the two members, the leading manufacturer will make decisions based on the retailers' feedback decisions, and then give his optimal decisions to the retailer to help the retailer make optimal decisions. In this way, we can obtain the decision sequence of the decentralized dual-channel closed-loop supply chain using the backward induction method by the following steps:

Step 1: Analyze the retailer's optimal decisions for the recovery rate of used products, the unit retail sales price and the retail service level in response to the manufacturer's decision variables.

Step 2: Feedback the retailer's decision information to the manufacturer, and then the manufacturer determines the optimal unit recovery price, the unit wholesale price and the unit direct sales price to maximize his profits.

Step 3: Insert the manufacturer's optimal decisions into retailer's feedback function, and obtain the retailer's optimal decisions that maximize his profits.

Therefore, through the above solution process, the optimal results for the decentralized dual-channel closed-loop supply chain can be obtained. Table 2 summarizes the optimal results.

The proof for the optimal results of the decentralized dual-channel closed-loop supply chain can be found in Appendix A.

Table 2 indicates that when consumers' e-commerce preferences are small, i.e., $0 \le \theta \le \theta_\alpha^R$, the market demand in the direct online channel will not be greater than zero, i.e., $Q_d^* \le 0$. The manufacturer only operates the offline retail channel. The sensitivities of all members' optimal decisions and profits with respect to parameters λ and β are shown in Corollaries 1 and 2. As consumers' e-commerce preferences increase to a certain range, i.e.,

$\max\left\{\theta_\alpha^R, 0\right\} < \theta < \min\left\{\theta_\beta^R, 1\right\}$, the manufacturer should open a direct online channel based on the offline retail channel. The market demand in the dual-channel system is $Q_{u-d}^* + Q_{u-t}^* = \frac{4C_L(\theta - c_n)}{8C_L\theta - (\Delta - A)^2}$, which is related to consumers' e-commerce preferences. The sensitivities of all members' optimal decisions and profits with respect to parameters θ, λ and β are shown in Corollaries 5, 6 and 7. If consumers' e-commerce preferences increase considerably, i.e., $\theta_\beta^R \leq \theta \leq 1$, the market demand in the offline retail channel is zero; therefore, the retailer does not sell products or provide retail services, and only recycles used products as a third party. Therefore, the manufacturer only operates the direct online channel. The sensitivities of all members' optimal decisions and profits with respect to parameter θ are shown in Corollary 3.

Corollary 1: If $0 \leq \theta \leq \theta_\alpha^R$, *the first-order derivations are* $\frac{\partial w_t^*}{\partial \lambda} = 0$, $\frac{\partial b_t^*}{\partial \lambda} = 0$, $\frac{\partial p_t^*}{\partial \lambda} > 0$, $\frac{\partial Q_t^*}{\partial \lambda} > 0$, $\frac{\partial \tau_t^*}{\partial \lambda} > 0$, $\frac{\partial s_t^*}{\partial \lambda} > 0$, $\frac{\partial \prod_t^{M*}}{\partial \lambda} > 0$, *and* $\frac{\partial \prod_t^{R*}}{\partial \lambda} > 0$.

Corollary 1 indicates that the manufacturer only operates the offline retail channel when consumers' e-commerce preferences are small, i.e., $0 \leq \theta \leq \theta_\alpha^R$. As the sensitivity of the service quality to the service level increases, consumers can gain more utility from retail services. Therefore, more of them can obtain a positive surplus by buying products, and so the retailer can obtain more revenue by increasing the unit retail price. Although raising the price reduces consumer surplus, which makes consumers who do not have high preferences have no intention to buy products. However, the number of consumers who receive a positive surplus increases due to better retail service. Therefore, the retailer should wholesale more products from the manufacturer and raise the unit retail price for sales. In addition, as the recovery rate of used products increases, the manufacturer remanufactures a higher proportion of used products, which is beneficial to reducing production costs and increasing ecological benefits. Meanwhile, the sensitivity of the service quality to the service level does not affect the unit wholesales price and the unit recovery price for the manufacturer that recycles used products from the retailer, but the manufacturer can obtain more profits due to the increased market demand and higher proportion of used products that are remanufactured. Then, the manufacturer's revenues and profits increase.

Corollary 2: If $0 \leq \theta \leq \theta_\alpha^R$ *,the first-order derivations are* $\frac{\partial w_t^*}{\partial \beta} = 0$, $\frac{\partial b_t^*}{\partial \beta} = 0$, $\frac{\partial p_t^*}{\partial \beta} < 0$, $\frac{\partial Q_t^*}{\partial \beta} < 0$, $\frac{\partial \tau_t^*}{\partial \beta} < 0$, $\frac{\partial s_t^*}{\partial \beta} < 0$, $\frac{\partial \prod_t^{M*}}{\partial \beta} < 0$, *and* $\frac{\partial \prod_t^{R*}}{\partial \beta} < 0$.

Corollary 2 indicates that when consumers' e-commerce preferences are small, i.e., $0 \leq \theta \leq \theta_\alpha^R$, the manufacturer only operates the offline retail channel. When the sensitivity of the service costs to the service level increases, the retailer provides a lower service level to reduce the uneconomical service costs, which makes it so that more consumers would obtain a negative surplus and so they give up buying products. Meanwhile, the retailer can lower the retail price to retain consumers, which decreases the retailer's revenues and profits. The recovery rate of used products also decreases. This is bad for remanufacturing and ecological benefits. In addition, although the unit wholesale price and the unit recovery price of the used products returned from the retailer are not affected, the manufacturer's profit decreases due to the lower market demand and fewer remanufactured products.

Corollary 3: If $\theta_\beta^R \leq \theta \leq 1$, *the first-order derivations are* $\frac{\partial b_d^*}{\partial \theta} = 0$, $\frac{\partial p_d^*}{\partial \theta} > 0$, $\frac{\partial Q_d^*}{\partial \theta} > 0$, $\frac{\partial \tau_d^*}{\partial \theta} > 0$, $\frac{\partial \Pi_d^{M*}}{\partial \theta} > 0$, *and* $\frac{\partial \Pi_d^{T*}}{\partial \theta} > 0$.

Corollary 3 indicates that the manufacturer only operates the direct online channel when consumers' e-commerce preferences are high, i.e., $\theta_\beta^R \leq \theta \leq 1$. As consumers' e-commerce preferences increase, they will obtain a positive surplus from buying products through the direct online channel. The manufacturer can obtain more revenue by increasing the unit direct sales price. Although this behavior reduces consumer surplus, which makes consumers who do not have high preferences have no willingness to buy products, the number of consumers who receive a positive surplus also increases since the number of consumers increase more due to their e-commerce preferences. Therefore, the manufacturer should produce more products for direct sales and raising the unit direct sales price, increases his profits. In addition, the recovery rate of used products improves, which is beneficial to reducing production costs and improving ecological benefits.

Corollary 4: Let $v_u^d = \frac{1}{2} + \frac{\beta(1-\theta) - \lambda^2}{2[2\beta(1-\theta) - \lambda^2]}$. *Then,* $v \geq v_u^d \Rightarrow U_t \geq U_d$ *or* $v < v_u^d \Rightarrow U_t < U_d$, *and* $\frac{\partial v_u^d}{\partial \lambda} < 0$ *or* $\frac{\partial v_u^d}{\partial \beta} > 0$, *respectively*.

The proof for Corollary 4 can be found in Appendix B.

Corollary 4 indicates that the manufacturer operates a dual-channel system including online and offline sales channels when consumers' e-commerce preferences are moderate, i.e., $\max\left\{\theta_\alpha^R, 0\right\} < \theta < \min\left\{\theta_\beta^R, 1\right\}$. If $v \geq v_u^d$, the surplus that these consumers receive in the offline retail channel is not less than that in the direct online channel, and so they choose the offline retail channel to buy products. If $v < v_u^d$, these consumers choose the direct online channel. In addition, as λ decreases and β increases, v_u^d and $Q_{u-d}^* - Q_{u-t}^* = \frac{4C_L(\theta - c_n)}{8C_L\theta - (\Delta - A)^2} - \frac{\beta(1-\theta)}{2\beta(1-\theta) - \lambda^2}$ increases. This means that more consumers choose the direct online channel to buy products when the sensitivity of the service quality to the service level becomes insensitive and the service sensitivity costs to the service level is sensitive.

Corollary 5: If $\max\left\{\theta_\alpha^R, 0\right\} < \theta < \min\left\{\theta_\beta^R, 1\right\}$, *the first-order derivations are* $\frac{\partial w_u^*}{\partial \theta} < 0$, $\frac{\partial b_u^*}{\partial \theta} = 0$, $\frac{\partial p_t^{u*}}{\partial \theta} < 0$, $\frac{\partial Q_{u-t}^*}{\partial \theta} > 0$, $\frac{\partial p_d^{u*}}{\partial \theta} > 0$, $\frac{\partial Q_{u-d}^*}{\partial \theta} > 0$, $\frac{\partial \tau_u^*}{\partial \theta} > 0$, $\frac{\partial s_u^*}{\partial \theta} > 0$, $\frac{\partial \prod_u^{M*}}{\partial \theta} > 0$, *and* $\frac{\partial \prod_u^{R*}}{\partial \theta} < 0$.

Corollary 5 indicates that the manufacturer operates the dual-channel system including online and offline sales channels when consumers' e-commerce preferences are moderate, i.e., $\max\left\{\theta_\alpha^R, 0\right\} < \theta < \min\left\{\theta_\beta^R, 1\right\}$. As consumers' e-commerce preferences increase, more consumers can obtain a positive surplus in the direct online channel, which is beneficial to the manufacturer to obtain more revenues by raising the unit direct sales price. Although consumer surplus is reduced since the unit direct sales price increases, and some consumers who do not have high preferences have no willingness to buy the products. However, the number of consumers increases more due to their increasing e-commerce preferences. Therefore, the number of consumers who receive more positive surplus in the direct online channel still increases. For this reason, the manufacturer should raise the unit direct sales price and produce more products for direct sales, which increase the manufacturer's profits. Simultaneously, the recovery rate of used products increases, which is beneficial to remanufacturing activities. First, it reduces the production costs and increases the manufacturer's profits. Second, it can increase the ecological benefits. In addition, as consumers' e-commerce preferences increase, the manufacturer should reduce the unit wholesale price, which causes the retailer to reduce the unit retail price and promote products in the offline retail channel. The retailer should provide a higher retail service level to attract more consumers to buy products through the offline retail channel. Although these actions increase the market demand in the offline retail channel, the retailer's profits decrease due to the reduce unit retail price and higher retail service costs.

Corollary 6: If $\max\left\{\theta_\alpha^R, 0\right\} < \theta < \min\left\{\theta_\beta^R, 1\right\}$, *the first-order derivation are* $\frac{\partial w_u^*}{\partial \lambda} = 0$, $\frac{\partial b_u^*}{\partial \lambda} = 0$, $\frac{\partial p_t^{u*}}{\partial \lambda} > 0$, $\frac{\partial Q_{u-t}^*}{\partial \lambda} > 0$, $\frac{\partial p_d^{u*}}{\partial \lambda} = 0$, $\frac{\partial Q_{u-d}^*}{\partial \lambda} < 0$, $\frac{\partial \tau_u^*}{\partial \lambda} = 0$, $\frac{\partial s_u^*}{\partial \lambda} > 0$, $\frac{\partial \prod_u^{M*}}{\partial \lambda} > 0$, *and* $\frac{\partial \prod_u^{R*}}{\partial \lambda} > 0$.

Corollary 6 indicates that the manufacturer operates a dual-channel system including online and offline sales channels when consumers' e-commerce preferences are moderate, i.e., $\max\left\{\theta_\alpha^R, 0\right\} < \theta < \min\left\{\theta_\beta^R, 1\right\}$. As the sensitivity of the service quality to the service level increases, consumers can gain more utility and surplus from retail services. The retailer will raise the unit retail price to obtain more revenue. Although consumer surplus is reduced due to the unit retail price increasing, and some of customers who do not have high preferences have no willingness to buy the product, the number of consumers who have a positive surplus increase more. Therefore, the retailer should order more products from the manufacturer to sell at retail while raising the unit retail price. On this basis, although the increased sensitivity of the service quality to the service level makes more consumers abandon the direct online channel, the unit wholesale price at which the manufacturer sells products to the retailer, the unit recovery price and the recovery rate are not affected, while the market demand in the offline retail channel increases. All of these reasons increase the manufacturer's revenues and profits.

Corollary 7: If $\max\left\{\theta_\alpha^R, 0\right\} < \theta < \min\left\{\theta_\beta^R, 1\right\}$, *then* $\frac{\partial w_u^*}{\partial \beta} = 0$, $\frac{\partial b_u^*}{\partial \beta} = 0$, $\frac{\partial p_t^{u*}}{\partial \beta} < 0$, $\frac{\partial Q_{u-t}^*}{\partial \beta} < 0$, $\frac{\partial p_d^{u*}}{\partial \beta} = 0$, $\frac{\partial Q_{u-d}^*}{\partial \beta} > 0$, $\frac{\partial \tau_u^*}{\partial \beta} = 0$, $\frac{\partial s_u^*}{\partial \beta} < 0$, $\frac{\partial \prod_u^{M*}}{\partial \beta} < 0$, *and* $\frac{\partial \prod_u^{R*}}{\partial \beta} < 0$.

Corollary 7 indicates that the manufacturer operates the dual-channel system including online and offline sales channels when consumers' e-commerce preferences are moderate, i.e., $\max\left\{\theta_\alpha^R, 0\right\} < \theta < \min\left\{\theta_\beta^R, 1\right\}$. As the sensitivity of the service cost to the service level increases, the retailer provides a lower service level to reduce the uneconomical service costs, which makes more consumers obtain a negative surplus such that they give up buying products. Meanwhile, the retailer lowers the unit retail price for its existing consumers, which decreases the retailer's revenues and profits. In addition, the unit wholesale price at which the manufacturer sells products to the retailer remains unchanged, and so the retailer's profits decrease. In addition, some consumers abandon the offline retail channel and choose the direct online channel to buy products since the unit retail price increased. When the unit direct sales price remains unchanged and the sales volume of the direct online channel increases, the manufacturer can gain more profits through the direct online channel. In addition, the unit wholesale price and the unit recovery price are not affected, and the market demand in the offline retail channel decreases. Therefore, the manufacturer's revenues and profits decrease.

Corollary 8: 1) $b_t^* > b_d^* = b_u^*$. *2)* $\tau_t^* > \tau_d^* = \tau_u^*$.

The proof for Corollary 8 can be found in Appendix C.

Corollary 8 indicates that in the decentralized systems, the unit recovery price at which the manufacturer recycles from the retailer is the highest in the offline sales channel systems, followed by the direct online and dual-channel systems. The sequence of the recovery rate of used products is the same as the sequence of the unit recovery price in the three kinds of sales channels. This is because that manufacturer's higher unit recovery price can inspire the retailer to recycle more used products to sell to the manufacturer.

From the above seven corollaries about the decentralized closed-loop supply chain, we find the following: 1) Consumers' e-commerce preferences are the main thing that influences the sales channel strategy. The manufacturer should open the direct online channel when consumers have higher e-commerce preferences, and they need to close the offline retail channel when consumers' e-commerce preferences significantly increase. Nevertheless, as the level of retail services increases, more consumers are attracted to buying products from the offline retail channel, which encourages the manufacturer to operate this channel. 2) When consumers' e-commerce preferences increase, the benefits for all members and the recovery rate in the dual-channel and direct online channel systems will increase. 3) Retail services are beneficial to the dual-channel and offline retail channel systems. When the sensitivity of the service quality to the service level increases and the sensitivity of the service costs to the service level decreases, the benefits for all members

TABLE 3. Channel selection strategy for a centralized closed-loop supply chain.

Channel strategy / Optimal results	$0 \le \theta \le c_n$ Offline retail channel	$c_n < \theta < 1-\lambda^2/2\beta$ Dual-channel	$1-\lambda^2/2\beta \le \theta \le 1$ Direct online channel
p_t^{C*}	$\frac{4C_L\beta(1-c_n)+2\left[2C_L(2\beta-\lambda^2)c_n-\beta(\Delta-A)^2\right]}{2\left[2C_L(2\beta-\lambda^2)-\beta(\Delta-A)^2\right]}$	$\frac{1+\theta}{2}+\frac{\lambda^2(1-\theta)}{2\left[2\beta(1-\theta)-\lambda^2\right]}-\frac{2C_L\theta(\theta-c_n)}{4C_L\theta-(\Delta-A)^2}$	---
p_d^{C*}	---	$\theta-\frac{2C_L\theta(\theta-c_n)}{4C_L\theta-(\Delta-A)^2}$	$\theta-\frac{2C_L\theta(\theta-c_n)}{4C_L\theta-(\Delta-A)^2}$
Q_t^{C*}	$\frac{4\beta C_L(1-c_n)}{2\left[2C_L(2\beta-\lambda^2)-\beta(\Delta-A)^2\right]}$	$\frac{\beta(1-\theta)}{2\beta(1-\theta)-\lambda^2}$	---
Q_d^{C*}	---	$\frac{2C_L(\theta-c_n)}{4C_L\theta-(\Delta-A)^2}-\frac{\beta(1-\theta)}{2\beta(1-\theta)-\lambda^2}$	$\frac{2C_L(\theta-c_n)}{4C_L\theta-(\Delta-A)^2}$
τ^{C*}	$\frac{\beta(\Delta-A)(1-c_n)}{2C_L(2\beta-\lambda^2)-\beta(\Delta-A)^2}$	$\frac{(\Delta-A)(\theta-c_n)}{4C_L\theta-(\Delta-A)^2}$	$\frac{(\Delta-A)(\theta-c_n)}{4C_L\theta-(\Delta-A)^2}$
s^{C*}	$\frac{2\lambda C_L(1-c_n)}{2C_L(2\beta-\lambda^2)-\beta(\Delta-A)^2}$	$\frac{\lambda(1-\theta)}{2\beta(1-\theta)-\lambda^2}$	0
Π^{C*}	$\frac{\beta C_L(1-c_n)^2}{2C_L(2\beta-\lambda^2)-\beta(\Delta-A)^2}$	$\frac{\beta(1-\theta)^2}{2\left[2\beta(1-\theta)-\lambda^2\right]}+\frac{C_L(\theta-c_n)^2}{4C_L\theta-(\Delta-A)^2}$	$\frac{C_L(\theta-c_n)^2}{4C_L\theta-(\Delta-A)^2}$

increase and the recovery rate in the system that contain the offline retail channel will increase. 4) The recovery rate of used products is the highest in the offline retail channel system due to the manufacturer's higher unit recovery price incentivizing the retailer.

V. COORDINATION ANALYSIS

Now we use the centralized closed-loop supply chain model to analyze the operational efficiency of the abovementioned decentralized dual-channel closed-loop supply chain. In the centralized dual-channel closed-loop supply chain, all members aim at maximizing the system profit. We assume that there is a centralized decision maker [29], [30]. We add (3) and (4) to gain the profit function of the centralized system as follows:

$$\Pi_u^C(p_d, p_t, \tau, s) = \left(p_t^C - c_n\right) Q_t^C + \left(p_d^C - c_n\right) Q_t^C + (\Delta - A)\,\tau Q^u - C_L\tau^2 - \frac{\beta s^2}{2} \quad (5)$$

The centralized decision maker aims to maximize the system profits by analyzing the recovery rate of used products, the retail sales price, the direct sales price and the retail service level at the same time. The optimal results of the centralized system are shown in Table 3.

Corollary 9: 1) $\tau_t^* < \tau_t^{C*}$, $s_t^* < s_t^{C*}$, and $\prod_t^* < \prod_t^{C*}$. 2) $\tau_u^* < \tau_u^{C*}$, $s_u^* < s_u^{C*}$, and $\prod_u^* < \prod_u^{C*}$. 3) $\tau_d^* < \tau_d^{C*}$, and $\prod_d^* < \prod_d^{C*}$.

The proof for Corollary 9 can be found in Appendix D.

Corollary 9 indicates that when the manufacturer only operates the offline retail channel, the recovery rate, service level and total profits of the decentralized system are less than those of the centralized system. When the manufacturer operates the dual-channels with the online and offline sales channels, the recovery rate, service level and total profits of the decentralized system are less than those of the centralized system. When the manufacturer operates the direct online channel, the recovery rate and total profits of the decentralized system are less than those of the centralized system. We can find that the "Double Marginalization" problem makes the economic and ecological benefits of the decentralized system weaker than those of the centralized system in the three kinds of sales channels. Therefore, we design a revenue-service cost sharing contract to solve this problem in a coordinated manner. The contract coordination mechanism is that the manufacturer and the retailer share the sales revenue, and the production, recovery and service costs at rates of $1-\rho$ and ρ, respectively [34], [44]. The profit functions of the manufacturer and the retailer coordinated by the revenue-service cost sharing contract are as (6) and (7), shown at the bottom of the next page.

Proposition 1: The unit direct sales price designed by the manufacturer is p_{u-t}^{C*}, and the revenue-service cost sharing contract parameters (w, b, ρ) meet $w_u^* = \rho^* c_n \frac{Q^u}{Q_t^u}$ and $b_u^* = \rho^*\Delta$. The retailer's profit function is an affine function of the centralized system, namely, $\Pi_u^R\left(p_t^u, \tau, s\right) = \rho^*\Pi_u^C(p_d, p_t, \tau, s)$, which means that the retailer's behavior can be coordinated. All members can obtain win-win Pareto profits by bargaining on the revenue and service cost sharing rate ρ in the following range in (8), as shown at the bottom of the next page.

Proposition 1 indicates that in order to solve the "Double Marginalization" problem and improve the operating efficiency of the decentralized closed-loop supply chain, the leading manufacturer should set the unit direct sales price

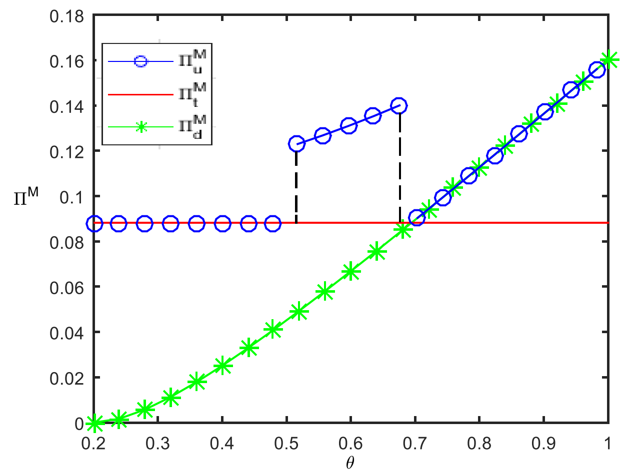

FIGURE 3. The impact of e-commerce preferences θ on the manufacturer's profits.

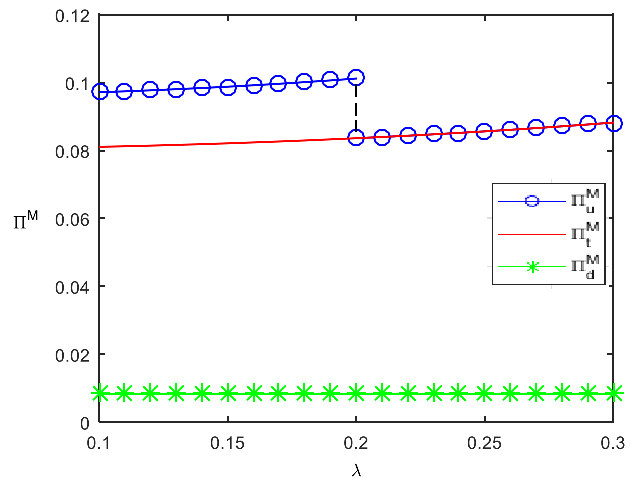

FIGURE 4. The impact of the sensitivity of the service quality to the service level λ on the manufacturer's profits.

as in the centralized system, and determine parameters of the revenue-service cost sharing contract to meet a certain condition in this proposition. Then, the manufacturer can guide the retailer to sell the same quantities of products at the same unit retail price as in the centralized system. In addition, there is a bargaining range for the revenue and service cost sharing rates for the manufacturer and the retailer. Both of them can obtain win-win profits by bargaining on the revenue and service cost sharing rates in this range. Finally, all members in the system can achieve win-win results, and the economic and ecological benefits can achieve the levels of those in the centralized system.

VI. NUMERICAL EXAMPLES

Numerical examples are given to illustrate the results derived throughout this paper. Referring to the related literature and similar research [26], and according to the actual situation, we fix the parameters as $c_n = 0.2$, $c_r = 0.1$, $A = 0.02$, and $C_L = 0.5$, which are also used in all the subsequent figures. Figures 3 to 5 show the results for the manufacturer's profits When the exogenous variables of consumers e-commerce preferences θ, service quality λ and service costs β change. The changes of the recovery rate of the used products with respect to consumers' e-commerce preferences θ, service quality λ and service costs β are shown in Figure 6. The contract coordination results are shown in Tables 4 and 5.

A. THE IMPACT OF E-COMMERCE PREFERENCE

The changes in the manufacturer's profits when consumers' e-commerce preferences increase are shown in Figure 3. We can find that consumers' e-commerce preferences have a positive impact on the manufacturer's profits in the dual-channel and direct online channel systems, which can be supported by Corollaries 3 and 5.

The manufacturer chooses the offline retail channel when $0 \le \theta < 0.55$, the dual-channels when $0.55 \le \theta < 0.7$, and the direct online channel when $0.7 \le \theta < 1$, respectively. This is because when consumers' e-commerce preferences are smaller, they will obtain less surplus from the direct sales channel ($U_d = \theta v - p_d^u$). Correspondingly, more consumers can receive more positive surplus through the offline retail channel ($U_t = v - p_t^u + \lambda s$) when their

$$\Pi_u^M(w, b, p_d, \rho) = (w - c_n) Q_t^u + [(1-\rho) p_d - c_n] Q_d^u + (1-\rho) p_t Q_t^u + (\Delta - b)\tau Q^u - (1-\rho) A\tau Q^u - (1-\rho) C_L \tau^2 - (1-\rho)\frac{\beta s^2}{2} \tag{6}$$

$$\Pi_u^R(p_t, \tau, s, \rho) = (\rho p_t - w) Q_t^u + \rho p_d Q_d^u + (b - \rho A)\tau Q^u - \rho C_L \tau^2 - \rho \frac{\beta s^2}{2} \tag{7}$$

$$\frac{\left[4C_L\theta - (\Delta - A)^2\right]\left\{8C_L(\theta - c_n)^2(\Delta - A)^2\left[2\beta(1-\theta) - \lambda^2\right] + \beta(1-\theta)^2\left[8C_L\theta - (\Delta - A)^2\right]^2\right\}}{4\left[8C_L\theta - (\Delta - A)^2\right]^2\left\{\beta(1-\theta)^2\left[4C_L\theta - (\Delta - A)^2\right] + 2C_L(\theta - c_n)^2\left[2\beta(1-\theta) - \lambda^2\right]\right\}}$$
$$\le \rho \le 1 - \frac{\left[4C_L\theta - (\Delta - A)^2\right]\left\{8C_L(\theta - c_n)^2\left[2\beta(1-\theta) - \lambda^2\right] + \beta(1-\theta)^2\left[8C_L\theta - (\Delta - A)^2\right]\right\}}{2\left[8C_L\theta - (\Delta - A)^2\right]\left\{\beta(1-\theta)^2\left[4C_L\theta - (\Delta - A)^2\right] + 2C_L(\theta - c_n)^2\left[2\beta(1-\theta) - \lambda^2\right]\right\}} \tag{8}$$

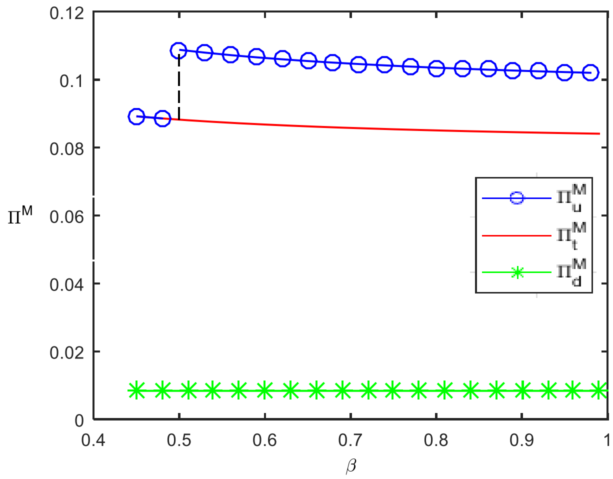

FIGURE 5. **The impact of the sensitivity of the service costs to the service level β on the manufacturer's profits.**

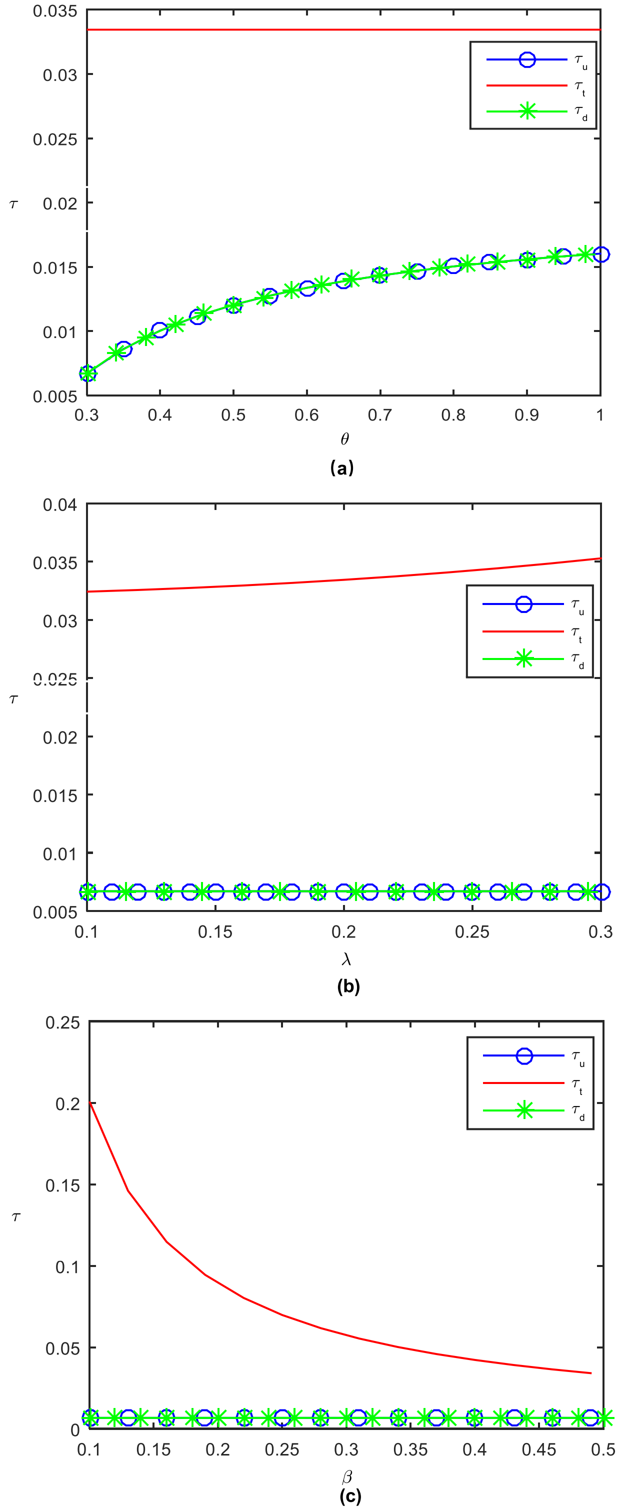

FIGURE 6. **Changes of the recovery rate. (a). The impact of e-commerce preferences θ. (b). The impact of the sensitivity of the service quality to the service level λ. (c). The impact of the sensitivity of the service costs to the service level β.**

e-commerce preferences are less than 0.55. Now, the manufacturer only operates the offline retail channel and his profits are not affected by consumers' e-commerce preferences. As consumers' e-commerce preferences increase, many of them can receive more positive surplus through the direct online channel. From Corollaries 3 and 5, we can find that the unit direct sale price and sales volume increase in the direct online channel, which will allow the manufacturer to obtain higher profit by opening direct sales channel based on the offline retail channel and operating the dual-channels. When consumers' e-commerce preferences are greater than 0.7, more consumers can receive more surplus by purchasing products in the direct online channel compared with the offline retail channel. Now, the manufacturer only operates the direct online channel and completely abandons the offline retail channel. Figure 3 proves that consumers' e-commerce preferences have the largest impact on manufacturers' sales channel strategy. As consumers' e-commerce preferences increase, the manufacturer should shift from the offline retail channel to the direct online channel.

B. THE IMPACT OF THE SENSITIVITY OF THE SERVICE QUALITY TO THE SERVICE LEVEL

The changes of manufacturer's profits when the sensitivity of the service quality to the service level increases are shown in Figure 4. We can find that the sensitivity of the service quality to the service level has a positive impact on the manufacturer's profits in the dual-channel and offline retail channel systems, which can be supported by Corollaries 1 and 6.

The manufacturer chooses the dual-channels when $0.1 \leq \lambda < 0.2$, and the offline retail channel when $0.2 \leq \lambda \leq 0.3$. This is because that when the service quality is less sensitive to the service level, i.e., $0.1 \leq \lambda < 0.2$, retail services will not provide more utility for consumers ($U_t = v - p_t + \lambda s$). Now, some consumers receive more positive surplus through the offline retail channel while some of them receive more positive surplus through online shopping. For this reason, the manufacturer can obtain the highest profits by opening the dual-channels with online and offline sales channels. As the

TABLE 4. Optimal results of the decentralized closed-loop supply chain.

Members' decisions / Operating channel	Retailer				Manufacturer				System
	$p_t^* \times (10^{-4})$	$s^* \times (10^{-4})$	$\tau^* \times (10^{-4})$	$\Pi_R^* \times (10^{-4})$	$p_d^* \times (10^{-4})$	$w^* \times (10^{-4})$	$b^* \times (10^{-4})$	$\Pi_M^* \times (10^{-4})$	$\Pi^* \times (10^{-4})$
Offline retail channel	8191.44	1323.33	176.44	441.11	--	6000	1000	882.22	1323.44
Direct online channel	--	--	143.18	1.03	4494.27	--	600	894.90	895.53
Dual-Channel	7065.70	2142.86	143.18	268.88	4494.27	5994.27	600	1430.62	1699.50

sensitivity of the service quality to the service level increases to a certain range, i.e., $0.2 \leq \lambda \leq 0.3$, we can easily find that λ positively affects $U_t(U_t = v - p_t + \lambda s)$. From corollary 4, we know that $\partial v_u^d/\partial\lambda < 0$. This means that more consumers can receive more surplus from the offline retail channel as λ increases in the dual-channel system, and so they will abandon the online direct channel and choose offline retail channel to buy products. Therefore, the high sensitivity of the service quality to the service level will cause manufacturer to close the direct online channel and only operate the offline retail channel to obtain the maximum profits. Figure 4 proves that the sensitivity of the service quality to the service level also has a certain influence on the manufacturer's channel strategy.

C. THE IMPACT OF THE SENSITIVITY OF THE SERVICE COSTS TO THE SERVICE LEVEL

The changes of manufacturer's profits when the sensitivity of the service costs to the service level increases are shown in Figure 5. We can find that the sensitivity of the service costs to the service level has a negative impact on the manufacturer's profit in the dual-channel and offline retail channel systems, which is contrary to the impact of the sensitivity of the service costs to the service level on the manufacturer's profit, and this can be supported by Corollaries 2 and 7.

The manufacturer chooses dual-channels when $0.5 \leq \beta < 0.1$, and the offline retail channel when $0.45 \leq \beta < 0.5$. This is because when the service costs are more sensitive to the service level ($0.5 \leq \beta \leq 1$), the retailer will not provide a higher service level to avoid bearing excessive costs. For this reason, some consumers receive more positive surplus through online shopping while some of them receive more positive surplus through offline shopping. For this reason, the manufacturer can obtain the most profits by opening dual-channels with online and offline sales channels. As the sensitivity of the service costs to the service level decreases to a certain range, i.e., $0.45 \leq \beta < 0.5$, from Corollaries 2 and 7, we know that parameter β negatively affects s_t^* ($\partial s_t^*/\partial\beta < 0$) and $U_t(U_t = v - p_t + \lambda s)$. This shows that as β decreases, the retailer's service level will improve and consumers' surplus from the offline retail channel will increase. From Corollary4, we know that $\partial v_u^d/\partial\beta > 0$. This means that more consumers will not receive much surplus by buying products through the direct online channel as the service level increases, and so they will abandon the online direct channel and choose the offline retail channel to buy products. Therefore, the low sensitivity of the service costs to the service level will cause the manufacturer to close the direct online channel and only operate the offline retail channel to obtain greater profits. Figure 5 proves that the sensitivity of the service quality to the service level also has a certain influence on the manufacturer's channel strategy.

D. THE IMPACTS OF E-COMMERCE PREFERENCES, AND, THE SENSITIVIES OF THE SERVICE QUALITY AND SERVICE COSTS TO THE SERVICE LEVEL ON THE RECOVERY RATE

From Figure 6(a), Figure 6(b), and Figure 6(c), we can find that the recovery rate of used products is the highest in the offline retail channel closed-loop supply chain system, followed by the direct online sales channel and the dual-channel closed-loop supply chain systems. This is also shown in Corollary 8. This result occurs because that retailer has more motivation to recycle used products when the manufacturer provides a higher unit recovery price. From figure 6(a), we can find that as consumers' e-commerce preferences increase, the recovery rates of used products increase in the direct online sales channel and dual-channel systems. The changes are also shown in Corollaries 3 and 5, respectively. This means that when consumers have higher e-commerce preferences, the dual-channel and direct online sales channel closed-loop supply chain systems can achieve better ecological benefits.

From Figure 6(b) and Figure 6(c), we can find that as the sensitivity of the service quality to the service level increases and the sensitivity of the service cost to the service level decreases, the recovery rate of used products increases in the offline retail channel system. The changes are also shown in Corollaries 1 and 2, respectively. This means that when consumers are more sensitive to the service level, and the retailer is less sensitive to the service costs, and the offline retail channel closed-loop supply chain system can achieve better ecological benefits.

E. COORDINATE ANALYSIS OF REVENUE-SERVICE COST SHARING CONTRACT

To verify the effectiveness of the contract coordination, the parameters θ, λ and β are assigned as following:$\theta = 0.7$, $\lambda = 0.3$, $\beta = 0.5$. The optimal results of the decentralized

TABLE 5. Coordinate results of the dual-channel closed-loop supply chain with the revenue-service cost sharing contract.

ρ_u Range	ρ_u Value	$w_u(\rho_u)\times(10^{-4})$	$b_u(\rho_u)\times(10^{-4})$	$\Pi_u^R(\rho_u)\times(10^{-4})$	$\Pi_u^M(\rho_u)\times(10^{-4})$	$\Pi_u^C\times(10^{-4})$
(0.14,0.64)	0.35	351.61	350	688.94	1279.45	1968.39
	0.45	452.07	450	885.77	1082.62	
	0.55	552.53	550	1082.62	885.77	

closed-loop supply chain are shown in Table 4. We can find that the manufacturer can obtain the most profits by operating the dual-channels with online and offline sales channels.

The coordinate results of the dual-channel closed-loop supply chain with the revenue-service cost sharing contract are shown in Table 5. We can find that the total profits of all members in the dual-channel system with the revenue-service cost sharing contract coordination are the same as those in the centralized systems. There is also a bargaining range (0.14, 0.64) for the revenue and service cost sharing rate. The manufacturer and the retailer can obtain win-win profits by bargaining on the revenue and service cost sharing rates in this range. The above numerical example proves Proposition 1.

VII. CONCLUSION AND MANAGERIAL INSIGHTS

The rapid development of e-commerce has caused consumers' shopping behaviors to change, which have a significant impact on manufacturer s' operating strategies. Increasingly more companies choose to open an online sales channel to meet consumers' e-commerce preferences. To cope with the competition from e-commerce platforms, retailers can provide retail services and may achieve win-win results. In addition, remanufacturing has been widely used to obtain higher economic and ecological benefits. Therefore, this work uses a dual-channel closed-loop supply chain to analyze the impacts of consumers' e-commerce preferences and retail services on the channel choice seeking to achieve higher economic and ecological benefits.

Some conclusions and managerial insights are given as follows: 1) Consumers' e-commerce preferences are the main item that influences a manufacturer's channel strategy. When consumers are more likely to purchase products through e-commerce platforms, the manufacturer should continue to increase their emphasis on the direct online channel while possibly abandoning the retail channel. 2) Retail services can make consumers have higher utility from buying products through the offline retail channel, thereby reducing the influence of the direct online channel caused by e-commerce preferences and helping maintain the offline retail channel. For this reason, many brick and mortar stores provide a large number of offline activities in reality. 3) The recovery rate of used products is positively related to consumers' e-commerce preferences and the service quality, while it is negatively related to service costs. Therefore, in order to fulfill their environmental responsibility, consumers should conduct e-commerce shopping and force enterprises to continuously improve their service capabilities to enhance service quality and reduce service costs. 4) The operating efficiency of the decentralized closed-loop supply chain is lower than that of the centralized system due to the selfish behaviors of the manufacturer and the retailer. Both of them can alleviate markup behavior using a revenue-service cost sharing contract, and can achieve win-win profits and improved ecological benefits from the closed-loop supply. This means that upstream and downstream companies have opportunities to negotiate to achieve win-win results.

This study generates insightful guidelines regarding the operating decisions and strategies considering consumers' e-commerce preferences and retail services in a closed-loop supply chain. In further research, we can consider the operating strategies of a closed-loop supply chain under asymmetric information regarding the demands and costs. On this basis, we can further research the free-riding behavior of retail services from e-commerce platforms, and research the operating strategies in a closed-loop supply chain. In addition, when the number of members in the closed-loop supply chain increases, how channel strategies are implemented will be an interesting and challenging issue.

APPENDIX A

When $0 \le \theta \le \theta_\alpha^R$, only offline retail channel exists, according to (1) and (2), the profit functions of the manufacturer and the retailer are as follows:

$$\Pi_t^M(w,b) = (w - c_n)\,Q_t + (\Delta - b)\,\tau Q_t \tag{A1}$$

$$\Pi_t^R(p_t,\tau,s) = (p_t - w)\,Q_t + (b - A)\,\tau Q_t - C_L\tau^2 - \frac{\beta s^2}{2} \tag{A2}$$

Taking the derivatives of $\Pi_t^R(p_t,\tau,s)$ with respect to p_t, τ and s, we have:

$$\frac{\partial \Pi_t^R(p_t,\tau,s)}{\partial p_t} = 1 - 2p_t + \lambda s + w - (b - A)\,\tau \tag{A3}$$

$$\frac{\partial \Pi_t^R(p_t,\tau,s)}{\partial \tau} = (b - A)\,(1 - p_t + \lambda s) - 2C_L\tau \tag{A4}$$

$$\frac{\partial \Pi_t^R(p_t,\tau,s)}{\partial s} = \lambda\,(p_t - w) + \lambda\,(b - A)\,\tau - \beta s \tag{A5}$$

The Hessian matrix of $\Pi_t^R(p_t,\tau,s)$ is as follow:

$$H_R=\begin{bmatrix}\frac{\partial^2\Pi_t^R(p_t,\tau,s)}{\partial p_t^2} & \frac{\partial^2\Pi_t^R(p_t,\tau,s)}{\partial p_t\partial\tau} & \frac{\partial^2\Pi_t^R(p_t,\tau,s)}{\partial p_t\partial s}\\ \frac{\partial^2\Pi_t^R(p_t,\tau,s)}{\partial\tau\partial p_t} & \frac{\partial^2\Pi_t^R(p_t,\tau,s)}{\partial\tau^2} & \frac{\partial^2\Pi_t^R(p_t,\tau,s)}{\partial\tau\partial s}\\ \frac{\partial^2\Pi_t^R(p_t,\tau,s)}{\partial s\partial p_t} & \frac{\partial^2\Pi_t^R(p_t,\tau,s)}{\partial s\partial\tau} & \frac{\partial^2\Pi_t^R(p_t,\tau,s)}{\partial s^2}\end{bmatrix}$$
$$=\begin{bmatrix}-2 & -(b-A) & \lambda\\ -(b-A) & -2C_L & \lambda(b-A)\\ \lambda & \lambda(b-A) & -\beta\end{bmatrix}\tag{A6}$$

We can obtain the determinant of the Hessian $|H_1(p_t,\tau,s)|=-2<0$, $|H_2(p_t,\tau,s)|=4C_L-(b-A)^2>0$, $|H_3(p_t,\tau,s)|=-\left[4C_L\beta-\beta(b-A)^2-2C_L\lambda^2\right]<0$. Hence, $\Pi_t^R(p_t,\tau,s)$ is jointly concave in p_t, τ and s. According to the first-order partial derivatives, i.e., $\frac{\partial\prod_t^R(p_t,\tau,s)}{\partial p_t}=0$, $\frac{\partial\prod_t^R(p_t,\tau,s)}{\partial\tau}=0$, $\frac{\partial\prod_t^R(p_t,\tau,s)}{\partial s}=0$. We obtain the best response functions are as follows:

$$p_t^*(w)=\frac{1-\theta+p_d+\lambda s+w}{2}\tag{A7}$$
$$\tau^*(b)=\frac{(b-A)(\theta-p_d)}{2C_L\theta}\tag{A8}$$
$$s^*(w)=\frac{\lambda(p_t-w)}{\beta(1-\theta)}\tag{A9}$$

Then, the manufacturer makes the decision about the optimal w according to (A7) - (A9).

By substituting p_t,τ and s into the manufacturer's profit function, i.e., (A1). The manufacturer's profit can be expressed as:

$$\prod_t^M(w,b)=(w-c_n)\frac{2C_L\beta(1-w)}{\left\{\beta\left[4C_L-(b-A)^2\right]-2C_L\lambda^2\right\}}+\frac{2C_L\beta^2(b-A)(\Delta-b)(1-w)^2}{\left\{\beta\left[4C_L-(b-A)^2\right]-2C_L\lambda^2\right\}^2}\tag{A10}$$

The second-order derivative is as follows:

$$\frac{\partial^2\prod_t^M\left(w,\tau^*,p_t^*,s^*\right)}{\partial w^2}=-4C_L\beta\frac{\left\{\beta\left[4C_L-(b-A)^2\right]-2C_L\lambda^2-\beta(b-A)(\Delta-b)\right\}}{\left\{\beta\left[4C_L-(b-A)^2\right]-2C_L\lambda^2\right\}^2}\tag{A11}$$

Hence, $\prod_t^M\left(w,\tau^*,p_t^*,s^*\right)$ is concave in w, we have:

$$w^{t*}=\frac{1+c_n}{2}\tag{A12}$$
$$b_t^*=\Delta\tag{A13}$$

Further, we obtain the $p_t^*, Q_t^*, \tau_t^*, s_t^*, \prod_t^{M*}$ and $\prod_t^{R*}$ in Table 2.

When $\theta_\beta^R\le\theta<1$, only direct online channel exists, according to (1) and (2), the profit functions of the manufacturer and the retailer are as follows:

$$\Pi_d^M(p_d,b)=(p_d-c_n)Q_d+(\Delta-b)\tau Q_d\tag{A14}$$
$$\Pi_d^T(\tau)=(b-A)\tau Q_d-C_L\tau^2\tag{A15}$$

Taking the second-order derivative of $\Pi_d^T(\tau)$ with respect to τ, we have:

$$\frac{\partial^2\Pi_d^T(\tau)}{\partial\tau^2}=-2C_L<0\tag{A16}$$

So, $\Pi_d^T(\tau)$ is concave in τ. According to the first-order derivative, i.e., $\frac{\partial\prod_d^T(\tau)}{\partial\tau}=0$, we obtain the best response function:

$$\tau=\frac{(b-A)(\theta-p_d)}{2C_L\theta}\tag{A17}$$

Then, the manufacturer makes the decision about the optimal p_d and b according to (A17).

By substituting τ to manufacturer's profit function, i.e., (A14), the manufacturer's profit can be expressed as:

$$\Pi_d^M(p_d,b)=\frac{(p_d-c_n)(\theta-p_d)}{\theta}+\frac{(\Delta-b)(b-A)(\theta-p_d)^2}{2C_L\theta^2}\tag{A18}$$

The second-order partial derivatives are as follows:

$$\frac{\partial^2\Pi_d^M(p_d,b)}{\partial p_d^2}=-\frac{2C_L\theta-(\Delta-b)(b-A)}{C_L\theta^2}\tag{A19}$$
$$\frac{\partial^2\Pi_d^M(p_d,b)}{\partial b\partial p_d}=\frac{(2b-A-\Delta)(\theta-p_d)}{C_L\theta^2}\tag{A20}$$
$$\frac{\partial^2\Pi_d^M(p_d,b)}{\partial p_d\partial b}=\frac{(2b-A-\Delta)(\theta-p_d)}{C_L\theta^2}\tag{A21}$$
$$\frac{\partial^2\Pi_d^M(p_d,b)}{\partial b^2}=-\frac{(\theta-p_d)^2}{C_L\theta^2}\tag{A22}$$

So, the determinant of the Hessian matrix can be described as follows:

$$H_M=\begin{bmatrix}\frac{\partial^2\Pi_d^M(p_d,b)}{\partial p_d^2} & \frac{\partial^2\Pi_d^M(p_d,b)}{\partial p_d\partial b}\\ \frac{\partial^2\Pi_d^M(p_d,b)}{\partial b\partial p_d} & \frac{\partial^2\Pi_d^M(p_d,b)}{\partial b^2}\end{bmatrix}=\begin{bmatrix}-\frac{2C_L\theta-(\Delta-b)(b-A)}{C_L\theta^2} & \frac{(2b-A-\Delta)(\theta-p_d)}{C_L\theta^2}\\ \frac{(2b-A-\Delta)(\theta-p_d)}{C_L\theta^2} & -\frac{(\theta-p_d)^2}{C_L\theta^2}\end{bmatrix}\tag{A23}$$

So, $\Pi_d^M(P_d,b)$ is jointly concave in p_d and b. According to the first-order partial derivatives, i.e., $\frac{\partial\Pi_d^M(p_d,b)}{\partial p_d}=0$, $\frac{\partial\Pi_d^M(p_d,b)}{\partial b}=0$. We obtain the best response functions as follows:

$$p_d^*=\theta-\frac{4C_L\theta(\theta-c_n)}{8C_L\theta-(\Delta-A)^2}\tag{A24}$$
$$b_d^*=\frac{\Delta+A}{2}\tag{A25}$$

Further, we obtain the $Q_d^*, \tau_d^*, s_d^*, \prod_d^{M*}$ and $\prod_d^{T*}$ in Table 2.

When $\max\left\{\theta_\alpha^R, 0\right\} < \theta < \min\left\{\theta_\beta^R, 1\right\}$, simultaneous operation of dual-channels, the profit functions of the manufacturer and the retailer are the same as (3) and (4).

Taking the derivatives of $\Pi_u^R\left(p_t^u, \tau, s\right)$ with respect to p_t, τ and s, we have:

$$\frac{\partial \prod_u^R\left(p_t^u, \tau, s\right)}{\partial p_t^u} = \frac{1-\theta-2p_t^u+p_d^u+\lambda s+w}{1-\theta} \quad \text{(A26)}$$

$$\frac{\partial \prod_u^R\left(p_t^u, \tau, s\right)}{\partial \tau} = (b-A)\left(1-\frac{p_d^u}{\theta}\right)-2C_L\tau \quad \text{(A27)}$$

$$\frac{\partial \prod_u^R\left(p_t^u, \tau, s\right)}{\partial s} = \frac{\lambda\left(p_t^u-w\right)}{1-\theta}-\beta s \quad \text{(A28)}$$

The Hessian matrix of $\Pi_u^R\left(p_t^u, \tau, s\right)$ is as follow:

$$H_R = \begin{bmatrix} \frac{\partial^2\Pi_u^R\left(p_t^u,\tau,s\right)}{\partial p_t^{u2}} & \frac{\partial^2\Pi_u^R\left(p_t^u,\tau,s\right)}{\partial p_t^u\partial\tau} & \frac{\partial^2\Pi_u^R\left(p_t^u,\tau,s\right)}{\partial p_t^u\partial s} \\ \frac{\partial^2\Pi_u^R\left(p_t^u,\tau,s\right)}{\partial\tau\partial p_t^u} & \frac{\partial^2\Pi_u^R\left(p_t^u,\tau,s\right)}{\partial\tau^2} & \frac{\partial^2\Pi_u^R\left(p_t^u,\tau,s\right)}{\partial\tau\partial s} \\ \frac{\partial^2\Pi_u^R\left(p_t^u,\tau,s\right)}{\partial s\partial p_t^u} & \frac{\partial^2\Pi_u^R\left(p_t^u,\tau,s\right)}{\partial s\partial\tau} & \frac{\partial^2\Pi_u^R\left(p_t^u,\tau,s\right)}{\partial s^2} \end{bmatrix} = \begin{bmatrix} \frac{-2}{1-\theta} & 0 & \frac{\lambda}{1-\theta} \\ 0 & -2C_L & 0 \\ \frac{\lambda}{1-\theta} & 0 & -\beta \end{bmatrix} \quad \text{(A29)}$$

We can obtain the determinant of the Hessian: $\left|H_1\left(p_t^u, \tau, s\right)\right| = -\frac{2}{1-\theta} < 0, \left|H_2\left(p_t^u, \tau, s\right)\right| = \frac{4C_L}{1-\theta} > 0, \left|H_3\left(p_t^u, \tau, s\right)\right| = -\frac{2C_L\left[2\beta(1-\theta)-\lambda^2\right]}{(1-\theta)^2} < 0$. Hence, $\Pi_u^R\left(p_t^u, \tau, s\right)$ is jointly concave in p_t^u, τ and s. According to the first-order partial derivatives, i.e., $\frac{\partial \prod_u^R\left(p_t^u,\tau,s\right)}{\partial p_t^u} = 0$, $\frac{\partial \prod_u^R\left(p_t^u,\tau,s\right)}{\partial \tau} = 0$, $\frac{\partial \prod_u^R\left(p_t^u,\tau,s\right)}{\partial s} = 0$, we obtain the best response functions:

$$p_t^u = \frac{\beta(1-\theta)\left(1-\theta+p_d^u+w\right)-\lambda^2 w}{\left[2\beta(1-\theta)-\lambda^2\right]} \quad \text{(A30)}$$

$$\tau = \frac{(b-A)\left(\theta-p_d^u\right)}{2C_L\theta} \quad \text{(A31)}$$

$$s = \frac{\lambda\left(1-\theta+p_d^u-w\right)}{\left[2\beta(1-\theta)-\lambda^2\right]} \quad \text{(A32)}$$

Then, the manufacturer makes the decision about the optimal w, p_d^u and b according to (A30) - (A32).

By substituting p_t^u, τ and s to the manufacturer's profit function (3), the manufacturer's profit can be expressed as:

$$\prod_u^M\left(p_d^u, w, b\right) = (w-c_n)\left(1-\frac{\beta\left(1-\theta+w-p_d^u\right)-\lambda^2}{\left[2\beta(1-\theta)-\lambda^2\right]}\right) + \left(p_d^u-c_n\right)\left(\frac{\beta\left(1-\theta+w-p_d^u\right)-\lambda^2}{\left[2\beta(1-\theta)-\lambda^2\right]}-\frac{p_d^u}{\theta}\right) + \frac{(\Delta-b)(b-A)\left(\theta-p_d^u\right)^2}{2C_L\theta^2} \quad \text{(A33)}$$

The second-order partial derivatives for the optimality are as follows:

$$\frac{\partial^2 \prod_u^M\left(p_d^u, w, b\right)}{\partial w^2} = \frac{-2\beta}{\left[2\beta(1-\theta)-\lambda^2\right]} \quad \text{(A34)}$$

$$\frac{\partial^2 \prod_u^M\left(p_d^u, w, b\right)}{\partial w\partial p_d^u} = \frac{2\beta}{\left[2\beta(1-\theta)-\lambda^2\right]} \quad \text{(A35)}$$

$$\frac{\partial^2 \prod_u^M\left(p_d^u, w, b\right)}{\partial w\partial b} = 0 \quad \text{(A36)}$$

$$\frac{\partial^2 \prod_u^M\left(p_d^u, w, b\right)}{\partial p_d^u\partial w} = \frac{2\beta}{\left[2\beta(1-\theta)-\lambda^2\right]} \quad \text{(A37)}$$

$$\frac{\partial^2 \prod_u^M\left(p_d^u, w, b\right)}{\partial p_d^{u2}} = \frac{-2\beta}{\left[2\beta(1-\theta)-\lambda^2\right]} - \frac{2C_L\theta-(\Delta-b)(b-A)}{C_L\theta^2} \quad \text{(A38)}$$

$$\frac{\partial^2 \prod_u^M\left(p_d^u, w, b\right)}{\partial p_d^u\partial b} = \frac{(2b-A-\Delta)\left(\theta-p_d^u\right)}{C_L\theta^2} \quad \text{(A39)}$$

$$\frac{\partial^2 \prod_u^M\left(p_d^u, w, b\right)}{\partial b\partial w} = 0 \quad \text{(A40)}$$

$$\frac{\partial^2 \prod_u^M\left(p_d^u, w, b\right)}{\partial b\partial p_d^u} = \frac{-(\Delta-2b+A)\left(\theta-p_d^u\right)}{C_L\theta^2} \quad \text{(A41)}$$

$$\frac{\partial^2 \prod_u^M\left(p_d^u, w, b\right)}{\partial b^2} = \frac{-\left(\theta-p_d^u\right)^2}{C_L\theta^2} \quad \text{(A42)}$$

The determinant of the Hessian matrix can be described as (A43), shown at the bottom of the next page.

We can obtain the determinant of the Hessian: $\left|H_1\left(w, p_d^u, b\right)\right| = -\frac{2\beta}{2\beta(1-\theta)-\lambda^2} < 0$, $\left|H_2\left(w, p_d^u, b\right)\right| = \frac{2\beta\left[2C_L\theta-(\Delta-b)(b-A)\right]}{C_L\theta^2\left[2\beta(1-\theta)-\lambda^2\right]} > 0$ and $\left|H_3\left(w, p_d^u, b\right)\right| = \frac{2\beta\left(\theta-p_d^u\right)^2\left\{(2b-A-\Delta)^2-\left[2C_L\theta-(\Delta-b)(b-A)\right]\right\}}{C_L^2\theta^4\left[2\beta(1-\theta)-\lambda^2\right]} < 0$. Hence, $\pi_u^M\left(p_d^u, w, b\right)$ is jointly concave in p_d^u, w and b. According to the first-order partial derivatives, i.e., $\frac{\partial \prod_u^M\left(p_d^u,w,b\right)}{\partial p_d^u} = 0$, $\frac{\partial \prod_u^M\left(p_d^u,w,b\right)}{\partial w} = 0$, $\frac{\partial \prod_u^M\left(p_d^u,w,b\right)}{\partial b} = 0$. We obtain the best response functions:

$$p_d^{u*} = \theta - \frac{4C_L\theta\left(\theta-c_n\right)}{8C_L\theta-(\Delta-A)^2} \quad \text{(A44)}$$

$$w_u^* = \frac{1+\theta}{2} - \frac{4C_L\theta\left(\theta-c_n\right)}{8C_L\theta-(\Delta-A)^2} \quad \text{(A45)}$$

$$b_u^* = \frac{\Delta+A}{2} \quad \text{(A46)}$$

Further, we obtain the p_t^{u*}, Q_{u-t}^*, Q_{u-d}^*, τ_u^*, s_u^*, $\prod_u^{M*}$ and $\prod_u^{R*}$ in Table 2.

According to (1), only when the $\frac{p_d^u}{\theta} + \lambda s \leq p_t^u \leq 1 - \theta + p_d^u + \lambda s$ condition is met, the dual-channel supply chain can be operated.

By substituting p_d^{u*}, s_u^* and p_t^{u*} into the conditional function $\frac{p_d^u}{\theta} + \lambda s \leq p_t^u \leq 1 - \theta + p_d^u + \lambda s$. We have (A47) and (A48), as shown at the bottom of the page.

APPENDIX B

Under the dual-channel supply chain:

$$U_t = v - p_t + \lambda s = v - \frac{1+\theta}{2} + \frac{4C_L\theta(\theta - c_n)}{8C_L\theta - (\Delta - A)^2} - \frac{\beta(1-\theta)^2}{2\left[2\beta(1-\theta) - \lambda^2\right]} + \lambda\frac{\lambda(1-\theta)}{2\left[2\beta(1-\theta) - \lambda^2\right]} \tag{B1}$$

$$U_d = \theta v - p_d = \theta v - \theta + \frac{4C_L\theta(\theta - c_n)}{8C_L\theta - (\Delta - A)^2} \tag{B2}$$

Based on (B1) and (B2), when $U_t \geq U_d$, we can obtain:

$$v \geq \frac{1}{2} + \frac{\beta(1-\theta) - \lambda^2}{2\left[2\beta(1-\theta) - \lambda^2\right]} \tag{B3}$$

when $U_t < U_d$, we can obtain:

$$v < \frac{1}{2} + \frac{\beta(1-\theta) - \lambda^2}{2\left[2\beta(1-\theta) - \lambda^2\right]} \tag{B4}$$

Let $v_u^d = \frac{1}{2} + \frac{\beta(1-\theta)-\lambda^2}{2[2\beta(1-\theta)-\lambda^2]}$. The first partial derivative of v_u^d respect to β and λ are as follows:

$$\frac{\partial v_u^d}{\partial \beta} = \frac{\lambda^2(1-\theta)}{2\left[2\beta(1-\theta) - \lambda^2\right]^2} > 0 \tag{B5}$$

$$\frac{\partial v_u^d}{\partial \lambda} = \frac{-4\lambda\left[3\beta(1-\theta) - 2\lambda^2\right]}{2\left[2\beta(1-\theta) - \lambda^2\right]} < 0 \tag{B6}$$

APPENDIX C

The difference of τ_t^* and τ_d^* can be shown as follows:

$$\tau_t^* - \tau_d^* = \frac{\beta(1-c_n)(\Delta - A)}{2\left[2C_L(2\beta - \lambda^2) - \beta(\Delta - A)^2\right]} - \frac{(\theta - c_n)(\Delta - A)}{8C_L\theta - (\Delta - A)^2} \tag{C1}$$

when $\theta = 1$, where $\tau_t^* - \tau_u^* = 4C_L\lambda^2 + 2\beta > 0$, therefore, $\tau_t^* > \tau_d^*$ is always holds. So we can obtain $\tau_t^* > \tau_d^* = \tau_u^*$.

APPENDIX D

The differences of τ_t^* and τ_t^{C*}, s_t^* and s_t^{C*}, $\prod_t^*$ and $\prod_t^{C*}$, τ_u^* and τ_u^{C*}, s_u^* and s_u^{C*}, $\prod_u^*$ and $\prod_u^{C*}$, τ_d^* and τ_d^{C*}, $\prod_d^*$ and $\prod_d^{C*}$ can be shown as follows:

$$\tau_t^{C*} - \tau_t^* = \frac{\beta(1-c_n)(\Delta - A)}{2\left[2C_L(2\beta - \lambda^2) - \beta(\Delta - A)^2\right]} > 0 \tag{D1}$$

$$H_M = \begin{bmatrix} \frac{\partial^2 \prod_u^M(p_d^u, w, b)}{\partial w^2} & \frac{\partial^2 \prod_u^M(p_d^u, w, b)}{\partial w \partial p_d^u} & \frac{\partial^2 \prod_u^M(p_d^u, w, b)}{\partial w \partial b} \\ \frac{\partial^2 \prod_u^M(p_d^u, w, b)}{\partial p_d^u \partial w} & \frac{\partial^2 \prod_u^M(p_d^u, w, b)}{\partial p_d^{u2}} & \frac{\partial^2 \prod_u^M(p_d^u, w, b)}{\partial p_d^u \partial b} \\ \frac{\partial^2 \prod_u^M(p_d^u, w, b)}{\partial b \partial w} & \frac{\partial^2 \prod_u^M(p_d^u, w, b)}{\partial b \partial p_d^u} & \frac{\partial^2 \prod_u^M(p_d^u, w, b)}{\partial b^2} \end{bmatrix}$$
$$= \begin{bmatrix} \frac{-2\beta}{\left[2\beta(1-\theta) - \lambda^2\right]} & \frac{2\beta}{\left[2\beta(1-\theta) - \lambda^2\right]} & 0 \\ \frac{2\beta}{\left[2\beta(1-\theta) - \lambda^2\right]} & \frac{-2\beta}{\left[2\beta(1-\theta) - \lambda^2\right]} - \frac{2C_L\theta - (\Delta - b)(b - A)}{C_L\theta^2} & \frac{(2b - A - \Delta)(\theta - p_d^u)}{C_L\theta^2} \\ 0 & \frac{-(\Delta - 2b + A)(\theta - p_d^u)}{C_L\theta^2} & \frac{-(\theta - p_d^u)^2}{C_L\theta^2} \end{bmatrix} \tag{A43}$$

$$\theta_\alpha^R = \frac{\left[8C_L\beta + 16C_L\beta c_n - 8C_L\lambda^2 - \beta(\Delta - A)^2\right] - \sqrt{\left[8C_L\beta + 16C_L\beta c_n - 8C_L\lambda^2 - \beta(\Delta - A)^2\right]^2 - 32C_L\beta\left[16C_L\beta c_n - 8C_L\lambda^2 c_n - \beta(\Delta - A)^2\right]}}{16C_L\beta} < \theta$$
$$< \theta_\beta^R = \frac{\left[8C_L\beta + 16C_L\beta c_n - 8C_L\lambda^2 - \beta(\Delta - A)^2\right] + \sqrt{\left[8C_L\beta + 16C_L\beta c_n - 8C_L\lambda^2 - \beta(\Delta - A)^2\right]^2 - 32C_L\beta\left[16C_L\beta c_n - 8C_L\lambda^2 c_n - \beta(\Delta - A)^2\right]}}{16C_L\beta} \tag{A47}$$

$$\left[8C_L\beta + 16C_L\beta c_n - 8C_L\lambda^2 - \beta(\Delta - A)^2\right]^2 - 32C_L\beta\left[16C_L\beta c_n - 8C_L\lambda^2 c_n - \beta(\Delta - A)^2\right] \geq 0 \tag{A48}$$

$$s_t^{C*} - s_t^* = \frac{\lambda C_L (1-c_n)}{2C_L(2\beta-\lambda^2) - \beta(\Delta - A)^2} > 0 \tag{D2}$$

$$\prod_t^{C*} - \prod_t^{*} = \frac{\beta C_L (1-c_n)^2}{4\left[2C_L(2\beta-\lambda^2) - \beta(\Delta - A)^2\right]} > 0 \tag{D3}$$

$$\tau_u^{C*} - \tau_u^* = \frac{4C_L\theta(\Delta - A)(\theta - c_n)}{\left(4C_L\theta - (\Delta - A)^2\right)\left(8C_L\theta - (\Delta - A)^2\right)} > 0 \tag{D4}$$

$$s_u^{C*} - s_u^* = \frac{\lambda(1-\theta)}{2\left[2\beta(1-\theta) - \lambda^2\right]} > 0 \tag{D5}$$

$$\prod_u^{C*} - \prod_u^{*} = \frac{\beta(1-\theta)^2}{8\left[2\beta(1-\theta) - \lambda^2\right]} + \frac{C_L(\theta - c_n)^2(\Delta - A)^2\left[1 - 4C_L\theta + (\Delta - A)^2\right]}{\left[4C_L\theta - (\Delta - A)^2\right]\left[8C_L\theta - (\Delta - A)^2\right]} > 0 \tag{D6}$$

$$\tau_d^{C*} - \tau_d^* = \frac{4C_L\theta(\Delta - A)(\theta - c_n)}{\left[4C_L\theta - (\Delta - A)^2\right]\left[8C_L\theta - (\Delta - A)^2\right]} > 0 \tag{D7}$$

$$\prod_d^{C*} - \prod_d^{*} = \frac{C_L(\theta - c_n)^2(\Delta - A)^2}{\left[4C_L\theta - (\Delta - A)^2\right]\left[8C_L\theta - (\Delta - A)^2\right]} > 0 \tag{D8}$$

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