

## Research Article

# Channel Competition and Coordination of E-Commerce Platforms under Low-Carbon Environment: A Cooperative Game Approach

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Received 8 March 2022; Revised 9 April 2022; Accepted 20 April 2022; Published 28 September 2022

Academic Editor: Liu Zhi

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The objective of “low-carbon supply chain” and the development of e-commerce platforms (as e-platform) has boosted the production and sales of low-carbon products. Although the e-platform’s involvement promotes the efficiency of low-carbon products circulation, it leads to channel competition and double marginalization. To mitigate these negative effects, in the context of low-carbon production, a three-player supply chain that contains a low-carbon manufacturer, an e-platform, and a retailer are investigated. By introducing the Stackelberg game and cooperative game theory, the supply chain is coordinated under a cooperative framework considering the commission rate of e-platforms. Subsequently, Mathematica is used for numerical simulation. The results show that intensified channel competition and excessive commission rates will lead to malicious price cuts by supply chain members, which is not conducive to the low-carbon production of manufacturers. Appropriate cooperation strategies can improve the value and identity of low-carbon products and optimize the supply chain system. For coordination of supply chain, three cooperative game-theoretic mechanisms can coordinate low-carbon dual-channel supply chain of the e-commerce platform (LCDESC) well under different situations. These findings provide managerial insights for managers of LCDESC.

## 1. Introduction

Recently, the social and economic impacts of carbon emissions have attracted widespread attention from the public [1]. To address these environmental issue, academia and industry usually adopt various methods to reduce the carbon emission such as recycling used products [2, 3] and developing green low-carbon technology [4]. Nowadays, expanding market demand by publicizing and selling low-carbon products online became a new way to reduce carbon emission [5]. With the development of Internet, consumers’ consumption behavior has changed dramatically, i.e., shopping online is sharply increasing. Many scholars have observed this phenomenon and conducted a series of research on such dual-channel supply chain. Li et al. established a traditional low-carbon dual-channel supply chain

consisting of a manufacturer’s direct channel and offline channel and found that dual-channel development contributes to growing the profits of the manufacturer under a limited risk aversion environment [6]. Zhou et al. investigated the joint emission reduction strategies in a dual-channel supply chain and found that involvement of the manufacturer’s direct channel contributes to heightening emission reduction efforts of manufacturer [7]. Similarly, Zhang et al. introduced the manufacturer’s direct channel into a dual-channel supply chain network and its work shows online channel results in low profit of the supply chain system but high carbon emission reduction [8]. Yu et al. also studied a traditional low-carbon dual-channel supply chain and analyzed how cost of carbon emission reduction, cost of low-carbon advertising effort, and sharing ratio of advertising effort affect the profit of supply chain [9]. Xin

et al. integrated low-carbon technological innovation with the traditional dual-channel supply chain and found the conditions which help increase the interests of both the manufacturer and the retailer [10]. Zhu et al. discussed a novel dual-channel supply chain consisting of one manufacturer, one offline retailer, and one online retailer under carbon tax policy [11]. Zhang et al. implemented BOPS (buy-online-and-pick up-in store) into a dual-channel low-carbon supply chain (DLSC) and then studied the coordination methods [12]. Above research studies on DLSC often refer to the offline channel and manufacturer's direct channel or online retailer, but lack of paying attention to the participation in e-commerce platform. In recent years, shopping on e-platform is a more sought-after way of consumers, its daily Internet activities (i.e., visits) and benefits brought by big data analysis can effectively enlarge the purchase conversion rate and ease the production cost pressure of low-carbon manufacturers [13]. Therefore, low-carbon products sold through e-platform can expand market share and improve consumers' acceptance of the products. Nevertheless, there is insufficient literature discussing how the dual-channel supply chain with the participation of an e-commerce platform (DESC) can promote carbon emission reduction.

The e-platform in dual-supply chain plays double agency roles simultaneously including manufacturer's re-seller and retailer's agent. Abhishek et al. divide the supply chain based on e-platform into two business modes; one is the agency selling mode, and the other is the reselling mode [14]. Specifically, the agency selling mode used by companies such as Amazon sets up an "environmental protection zone" on their website which helps retailers to sell low-carbon products. The e-platform within agency selling mode merely provides a trading place and charges a certain commission fee, which is used to cover the cost of the platform's operation. While reselling mode requires e-platform to buy low-carbon products from manufacturer firstly and then sell them to consumers. This kind of mode is also known as the self-operated model (Table 1 is listed to distinguish two modes). Wang et al. studied consumers' acceptance of hybrid platforms based on a previous research, but they did not take into account the offline retailer's influence in the e-platform [15]. Actually, the relationship between the retailer and e-platform is crucial and complex because they are all important ways for a manufacturer to sell low-carbon products, so there exists a fierce competition. Xu et al. investigated the relationship between e-platform and manufacturer, and they proposed the "e-platform power" to represent the competitiveness of the platform [16]. Xu et al. found that the e-platform will encroach the retailer demand under reselling mode, and both marketplace mode and reselling mode can promote the income of the supply chain system when "e-platform power" is low [17]. Tian et al.' study fills in the gap in the abovementioned research studies and investigated an upstream competition among suppliers, but they do not research the channel competition among downstream members of e-commerce supply chain [18]. Considering channel competition between the retailer and platform, Cao et al. examined whether offline retailers need to enter e-platforms [19]. The abovementioned research points out the competitive relationship between retailers and e-platforms on DESC and the double marginalization effect caused by this relationship. It also

judges the applicable scenarios of various dual-channel structures through a game theory. However, little literature use coordination to study the cooperation between retailers and platforms on DESC, the studies of coordination on DLSC are fewer. Our research can make up for this gap.

Cooperation is regarded as a good solution to coordinate and manage complex supply chain issues, such as channel competition and double marginalization effect [20]. This business behavior pools their information and resources to achieve a win-win situation [21, 22]. Researchers have mainly designed two ways of coordination mechanisms: one is to design contracts and the other is to resort to a cooperative game theory. Ingene et al. used various two-part tariffs with constant per-unit charges to coordinate the supply chain with retailer competition [23]. Dong et al. designed a revenue-sharing contract to coordinate a two-period supply chain based on the e-platform [24]. Han et al. introduced the joint allocation contract of cost and profit to coordinate the low-carbon e-platform supply chain considering government subsidies and fairness concerns [25]. The work of Li et al. showed revenue-sharing contract and cost-sharing contract cannot always coordinate dual-channel low-carbon supply chain [26]. Peng et al. considered a "contract of revenue-sharing with subsidy on emission reduction" to coordinate a supply chain with yield uncertainty and low-carbon preference [27]. Moreover, Wang et al. coordinated a green e-platform supply chain by the "cost-sharing joint commission contract" [5]. Contracts can always distribute the surplus profits in a two-player supply chain, but it cannot work in a three-player supply chain. Such shortcoming is ameliorated by the cooperative game theory [28]; it successfully solves the problem of multiplayer or multilevel supply chain coordination through TU (transferable utility) games [21]. Although it has been well developed, its application in supply chain coordination is relatively limited [21, 28]. Therefore, the cooperative game theory is introduced into this paper for profit distribution mechanisms to address the issue of three-player supply chain coordination. Among cooperative games, the Shapley value mechanism (SVM) [29], the solidarity value mechanism [30], and the center-of-gravity of the imputation-set value (CISV) [31] are feasible solutions. The Shapley value is represented by utilitarianism and the solidarity value is SVM's improved method, while CISV is a kind of egalitarian which is called the consensus value [32, 33]. So, which kind of mechanism is more popular for supply chain members on DESC and can promote the selling of low-carbon products is the crucial issue that should be investigated.

Based on the review and Table 2, there are three gaps identified. First, the above investigation of dual-channel supply chain ignored the intervention of the e-platform. Second, previous research rarely considers the coordination on the DESC. Third, while coordinating the low-carbon DESC (LCDESC), relevant research studies still focus on designing contracts rather than cooperative games. For these research gaps, three key issues are researched in this paper: (1) the impact of channel competition and commission rate on DESC; (2) which cooperate strategy can promote low-carbon products and profitability of the supply chain system; and (3) how to choose a mechanism to distribute the surplus profit.

TABLE 1: Two e-commerce modes and their offline prototypes.

	Marketplace mode	Reselling mode
Business methods	Build a trading place for buyers and sellers, gather and sell customer flow, and obtain gross profit through transaction commissions from retailers and distributors.	Select and purchase branded products, sell them in their own channels, and obtain gross profit through the price difference between buying and selling.
Operational focus	Customer flow is the most important thing	Provide a wide variety of genuine products and better warehousing distribution services
Business essence	Traffic business for venue rental	Retail business
Online example	Taobao, tmall, pinduoduo	Suning.com
Offline prototype	Wanda commercial plaza, yiwu small commodity city	Wangfujing department store

TABLE 2: Literature positioning of this research (Y=Yes; N=No).

Reference	e-platform?	Dual-channel low-carbon supply chain?	Cooperative game approaches?
Zhou et al. [7]	N	Y	N
Zhang et al. [8]	N	Y	N
Zhu et al. [11]	N	Y	N
Yu et al. [9]	N	Y	N
Li et al. [6]	N	Y	N
Xin et al. [10]	N	Y	N
Zhang et al. [16]	N	Y	N
Abhishek et al. [14]	Y	N	N
Wang et al. [15]	Y	N	N
Tian et al. [18]	Y	N	N
Cao et al. [19]	Y	N	N
Xu et al. [16]	Y	N	N
Zheng et al. [38]	N	N	Y
Ingene et al. [23]	Y	N	N
Liu et al. [21]	N	N	Y
Zheng et al. [22]	N	N	Y
Zheng et al. [38]	N	N	Y
Dong et al. [24]	Y	N	N
Han et al. [25]	Y	Y	N
Wang et al. [5]	Y	Y (green supply chain)	N
This research	Y	Y	Y

To address these issues, the Stackelberg game and cooperative game are adopted to investigate the cooperative strategies and profit distribution. The paper mainly contributes to enrich the theoretical research of platform operation and application of the cooperative game theory. Specifically, it can be divided into the following three aspects. First, we found that low-carbon does not exactly equal high prices. It depends on cooperative strategies. Second, commission rate and channel competition affect the willingness of e-platform to cooperate. Third, the manufacturer gets the highest profit under the Shapley value mechanism and the solidarity value mechanism, while e-platform can maximize its profit under the CISV.

## 2. Problem Description

The three-player LCDESC containing a manufacturer (M), an e-platform (P), and an offline traditional retailer (R) is applied to this investigation. A precondition is that consumers who possess low-carbon awareness are willing to pay more for low-carbon products. In decentralized decision making, M

produces low-carbon products and wholesales them to P and R. P then retails the products to the end market, while R retails them at their offline stores and online flagship stores separately. In Table 3, we introduce commission fees into LCDESC as the condition that exists in an online flagship store. This decentralized setting is led by M; P and R are followers synchronously. Our key issue is to coordinate this three-player LCDESC under the cooperative framework.

To further research the cooperative strategy and application of the cooperative game, all cooperative forms are investigated first and equilibrium results follow. Given the formation of LCDESC, both P and R being distributors to the manufacturer are assumed, so they share the same wholesale price. Five models including the decentralized model (DC) are shown in Figure 1. With the above description and assumption, we established five coalition structures, a decentralized model DC that each player pursues personal maximum profit and makes decisions from M to P and R, a centralized model (CC) is a grand coalition which promotes all members to make decisions together for

TABLE 3: The composition of commission fees for major platforms.

Electronic business platform	Composition of commissions fees	Data sources
Tmall	Software service annual fee and real-time deduction of software service fee	“Tmall entry standard”
Tmall International	Software service annual fee and real-time deduction of software service fee	“Tmall International 2020 annual fee list of various technical service fees”
JD.com	Platform usage fee and technical service fee	“The list of various tariffs of JD.com open platform in 2020”
Koala overseas purchase	Technical service fee	Koala’s official website investment cooperation

pursuing the maximum profit of the whole system, and three fractional coalitions MP, MR and RP where these three are established and make consistent decisions within their own coalitions, respectively. In these partial cooperative models, the coalition MP (MR or RP) is regarded as an agent of a new interest group and divides members of LCDESC into two players such as MR and P. Under this situation, the coalition MP or MR (RP) is the leader (follower) and the other partner P or R ( $M$ ) is the follower (leader). Here, models CC and DC work as benchmark models.

From equilibrium results under different models, the characteristic functions of the cooperative game are obtained. Then, three coordination mechanisms of the cooperative game theory are proposed to distribute surplus profit among the three LCDESC players. Moreover, the numerical simulations are examined to evaluate the performance of cooperative strategies and conclude effective managerial insights for LCDESC management.

In the next section, we present our assumptions to make the research issue more prominent.

### 3. Notations and Assumptions

It is assumed that the same kind of low-carbon product circulates in the same LCDESC system. Based on the problem representations, we set the typical symbols and notations right through this paper as shown in Table 4:

For the convenience of analysis, we make the following assumptions.

- (1) For the convenience of calculation, we assume that the manufacturer’s unit production cost is 0, which does not affect the relevant conclusions of this article.
- (2) We assume that the consumers buy the same low-carbon product in the dual channel.
- (3) The members of LCDESC are all risk-neutral, and they are all rational economic men who pursue maximum profit.
- (4) Although the e-platform is developing rapidly, the report from the Chinese Ministry of Commerce shows that offline retailers still have a larger market share than e-commerce platforms; thus, we assume

that the e-commerce platform is not the focal firm in LCDESC and it shows weak power.

- (5) It is assumed that the manufacturer has the same wholesale price in the dual channel  $w_r = w_p = w$ . That is because the retailer and platform play the same role for the manufacturer [34, 35].
- (6) The cost of carbon abatement for manufacturers is  $C = 1/2ns^2$ , assuming  $n = 1$  for simple calculation [27].
- (7) Consumers are heterogeneous in their preference for the different channels, which are uniformly distributed between 0 and 1. Consumers will purchase the low-carbon product from online and offline channels, resulting in a demand function of the dual channel, [36, 37]:

$$\begin{cases} Q_r = \delta a - P_R + bP_P + \alpha s, \\ Q_p = (1 - \delta)a - P_P + bP_R + \alpha s. \end{cases} \quad (1)$$

- (8) To ensure profit of the retailer, it is assumed that  $p_r^y - w > \lambda p_r^y$ . This assumption allows  $R$  to have an incentive to deal with the platform and provides an economically feasible condition for the establishment of a marketplace-mode-based platform.
- (9) Assuming that the e-platform charges the commission fee based on a certain percentage of the retailer’s sales, the commotion rate  $0 < \lambda < 1$ , and then the amount of commission charged by the e-commerce platform is  $\lambda P_R^y Q_r$ .

### 4. Model Establishment

Then, we establish all possible models and derive the equilibrium results of these models.

*4.1. Decentralized Model (Model DC).* In this case, the supply chain leader  $M$  decides the wholesale price  $w$  and low-carbon level of the product  $s$  first. Then, the followers  $R$  and  $P$  decide the retailing price in the dual channel, respectively. Therefore, the players’ profit maximization function is given as follows:

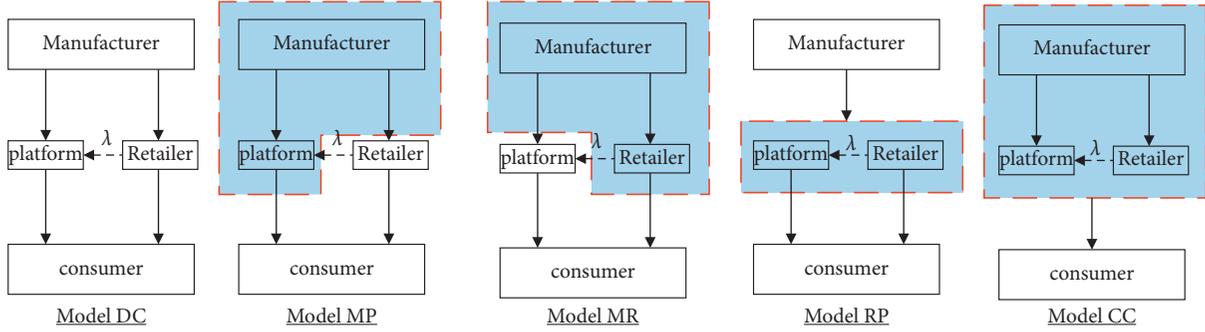


FIGURE 1: Noncooperative and cooperative models of LCDESC.

TABLE 4: Parameters and decision variables.

Notations	Definitions
$s$	Low-carbon level of products
$P_X^Y$	The retail price of player or coalition $x$ in model $y$ , $X \in \{M, P, R, MP, MR, PR, SC\}$ ; $Y \in \{DC, MP, MR, PR, CC\}$
$\delta$	Consumer offline preference coefficient
$a$	Market sharing
$b$	Cross-price sensitivity
$\alpha$	Consumer carbon emission reduction preference coefficient
$w_p$	The wholesale price of the e-platform
$w_r$	The wholesale price of the retailer
$1/2ns^2$	The cost of carbon emission reduction
$\lambda$	Commission rate
$Q_r$	Quantity of selling in the offline channel
$Q_p$	Quantity of selling in the online channel
$\pi_X^Y$	The profit of player or coalition $x$ in model $y$

$$\max \pi_M^{\text{DC}} = w(Q_r + Q_p) - \frac{1}{2}s^2$$

$$\begin{cases} \text{s.t. } \max \pi_R^{\text{DC}} = (P_R^{\text{DC}} - w)Q_r - \lambda P_R^{\text{DC}}Q_r \\ \text{s.t. } \max \pi_P^{\text{DC}} = (P_P^{\text{DC}} - w)Q_p + \lambda P_R^{\text{DC}}Q_p \end{cases} \quad (2)$$

Equation (2) characterizes the Stackelberg game for Model DC. Here,  $M$ ,  $R$ , and  $P$  maximize their profits and decision variables are the prices of retailer and platform. This

decentralized model is referred to as the noncooperative mechanism and serves as a bottom-line benchmark for our comparative studies. Proposition 1 furnishes the equilibrium result for this case.

**Proposition 1.** When  $\alpha^2 < 4(2 - \lambda + b)(1 - b)[4 - (1 + \lambda)b^2]/(1 - \lambda)[4 - b(-2 + \lambda + \lambda b)]^2$ , then the equilibrium pricing decisions are obtained as  $P_R = az/k$ ,  $P_P = a(x + y)/k$ ,  $w = a(1 - \lambda)[4 - (\lambda + 1)b^2(2 + S)]/k$ ,  $s = \alpha\alpha(1 - \lambda)[4 + b(2 - (1 + b)\lambda)](2 + S)/k$ . The resulting optimal profits are derived as  $\pi_M = 1/2ka^2(1 - \lambda)(2 + S)^2$ ,

$$\pi_P = \frac{a^2}{k^2} \left\{ \begin{aligned} & \alpha^2 \{ (1 - 2\delta)(1 - \lambda) \{ (b[\lambda(1 + b) - 2]) - 4 \} + (1 - b) \{ x + y + (2 + S)(1 - \lambda) [ (1 + \lambda)b^2 - 4 ] \} \} \\ & \left\{ 11 - 8\delta(2 - \lambda) - \lambda(9 - 2\lambda) + b \left\{ \begin{aligned} & 4 + 2[2 - \delta(5 - \lambda)]\lambda + \\ & \delta[4 + 3(1 - \lambda)\lambda]b - (1 - \delta)\lambda(3 + \lambda)b^2 \end{aligned} \right\} \right\} \\ & + z\lambda \{ 8 + z + b[4 - (2 + S)(1 + \lambda)b] - 6\lambda b^2 - 4(1 - \lambda\delta b)\lambda\delta b \} \end{aligned} \right\}, \quad (3)$$

$$\pi_R = \frac{a^2(1 - \lambda)}{k^2} \left\{ \begin{aligned} & z - \alpha^2 \{ 2(1 - 2\delta) \{ 4(1 - \lambda) + [(2 - \lambda)(\lambda - 1)]b + (1 - \lambda)\lambda b^2 \} \} + \\ & b\delta \{ 32 - 24\lambda + 2[(5 - \lambda)\lambda + 4]b + [\lambda(3\lambda - 1) - 8]b^2 - \lambda(1 + \lambda)b^3 \} \end{aligned} \right\}^2, \\ & + 4(3\lambda - 5) + (4 - 8\lambda)b + (7 + \lambda - 2\lambda^2)b^2 + \lambda(1 + \lambda)b^3$$

where  $y = 4[5 + 2\delta(\lambda - 2) + \alpha^2(2\delta - 1)(1 - \lambda) - 3\lambda]$ ,  $S = b[1 - \delta\lambda - (1 - \delta)\lambda b]$ ,  $z = \lambda[\alpha^2(3 - \lambda)(1 - \lambda) + 2\lambda - 1] - 7$ ,  $k = \alpha^2(1 - \lambda)[4 + (2 - \lambda)b - \lambda b^2] + 4(1 - b) - [4(2 - \lambda) + 4b + (2 + \lambda - \lambda^2)b^2 - (1 + \lambda)b^3]$ ,

$$x = \alpha^2 b \{(2\delta - 1)(1 - \lambda)\{2 - 5\lambda + b[\lambda + \lambda b - 3]\}\} + b \left\{ \begin{array}{l} 8\lambda - 4 - 2\delta(3\lambda + \lambda^2 - 8) + \\ [2\lambda^2 + \delta(4 + \lambda + \lambda^2) - 7 - \lambda]b \\ + [\delta(\lambda - 4) - \lambda](1 + \lambda)b^2 \end{array} \right\}. \quad (4)$$

*Proof.* The proof is furnished in Appendix A.  $\square$

**4.2. Centralized Model (Model CC).** In model CC, we considered uniting all players of the LDEDSC for maximizing the whole supply chain's profit. In this case, no financial transactions will occur among three members and the central planner sells low-carbon products to the end market directly. The channel profit function is formulated as follows:

$$\pi_{SC}^{CC} = P_P^{CC} Q_p + P_R^{CC} Q_r - \frac{1}{2}s^2. \quad (5)$$

We can see from equation (6) that commission is offset in this model, and the central planner makes the retail pricing decisions for products to maximize the channel profit. By first-order conditions, we have the following result.

**Proposition 2.** When  $b + \alpha^2 < 1$ , in the centralized model, the channel profit and the optimal selling prices are given as follows:  $P_P^{CC} = a[2 - \alpha^2 - 2(1 - b - \alpha^2)\delta]/4(1 + b)(1 - b + \alpha^2)$ ,  $P_R^{CC} = a[(2b + \alpha^2) + 2\delta(1 - b - \alpha^2)]/4(1 + b)(1 - b - \alpha^2)$ ,  $s = a\alpha/2(1 - b - \alpha^2)$ ,  $\pi_{CC} = a^2 \left[ \begin{array}{l} 2 - \alpha^2(1 - 2\delta)^2 \\ + 4(1 - b)(\delta - 1)\delta \end{array} \right] / 8(1 + b)(1 - b - \alpha^2)$

*Proof.* See Appendix B.  $\square$

**4.3. M and P Form the Coalition (Model MP).** In the model MP, M and P build a new coalition and are considered as a new decision maker who decides the price of the platform  $P_P^{MP}$ , wholesale price  $w$ , and carbon reduction level  $s$ . Subsequently, R sets its retail price  $P_R^{MP}$ . Similarly, the MP

coalition and retailers pursuit to maximize their profits. MP is the leader and the retailer is the follower. Besides, the retailer needs to pay commissions to the coalition. So, we set the profit function as follows and the optimal equilibrium solution is given in Proposition 3:

$$\begin{aligned} \max \pi_{MP}^{MP} &= wQ_r + P_P^{MP} Q_p - \frac{1}{2}s^2 + \lambda P_R^{MP} Q_r, \\ \text{s.t. } \max \pi_R^{MP} &= (P_R^{MP} - w)Q_r - \lambda P_R^{MP} Q_r. \end{aligned} \quad (6)$$

**Proposition 3.** When  $\alpha^2 \in (2 - 1/2(2 + \lambda)b^2/1 + \lambda + 1/4b(4 + 4\lambda + b), 2(2 - \lambda)(1 - b)/3 - \lambda + (1 - \lambda)b)$ , and then,  $s = a\alpha[2 - \delta - \lambda + \delta\lambda + (1 - \lambda)\delta b]/h$ ,  $w = 2a(1 - \lambda)\{[2\delta + \alpha^2(1 - 2\delta)](1 - \lambda) + b[2(1 - \delta)(2 - \lambda) + \alpha^2(1 - 2\delta)(1 - 2\lambda) + 2\delta\lambda b]\}/2(1 + b)h$ ,  $P_P^{MP} = a[\alpha^2(2\delta - 1) + 2(1 - \delta)(2 - \lambda) + 2\delta(2 - \lambda)b]/2(1 + b)h$ ,  $P_R^{MP} = a\{[2\delta + \alpha^2(1 - 2\delta)](3 - 2\lambda) + 2b[(1 - \delta)(2 - \lambda) + \alpha^2(1 - 2\delta)(1 - \lambda) + \delta(1 - \lambda)b]\}/2h(1 + b)$ ,  $\pi_R^{MP} = a^2(1 - \lambda)[\alpha^2(2\delta - 1) + 2\delta b - 2\delta]^2/4h^2$ ,  $\pi_{MP}^{MP} = a^2 \left\{ \begin{array}{l} 2\{2 - \delta[4 - \delta(3 - \lambda) - 2\lambda] - \lambda\} + 2\delta b \\ [2(1 - \delta)(2 - \lambda) + \delta(1 - \lambda)b] - \alpha^2(1 - 2\delta)^2 \end{array} \right\} / 4h(1 + b)$ . Among them,  $h = 4 + \alpha^2(\lambda - 3) - 2\lambda + [2(\lambda - 2) + \alpha^2(\lambda - 1)]b$

*Proof.* See Appendix C.  $\square$

**4.4. M and R Form the Coalition (Model MR).** In this case, we considered the manufacturer and retailer as a coalition and they decide the wholesale price  $w$ , carbon reduction level  $s$ , and the retail price  $P_R^{MR}$  together. After that, the platform sets the price of the platform  $P_P^{MR}$  alone. As the same as the assumption mentioned above, the coalition and platform pursue the maximized profit. Furthermore, the coalition MR needs to pay commissions to the platform. We established the profit function as follows:

$$\begin{aligned} \max \pi_{MR}^{MR} &= wQ_p + P_R^{MR} Q_r - \lambda P_R^{MR} Q_r - 1/2s^2, \\ \text{s.t. } \max \pi_P^{MR} &= (P_P^{MR} - w)Q_p + \lambda P_R^{MR} Q_r. \end{aligned} \quad (7)$$

**Proposition 4.** When  $\alpha^2 \in (8 - 4(1 + \lambda)b^2/(1 - \lambda)(2 + b)^2, 4 - 4b/3 - 2\lambda + (1 - 2\lambda)b)$ , we obtain the results including the wholesale price, the price of sale, and the profit of channel as follows:

$$\begin{aligned} s &= \frac{a\alpha\{1 + (1 - 2\lambda)[\delta + (1 - \delta)b]\}}{h}, \\ w &= \frac{a\{4(1 - \delta)(1 - \lambda b^2) - (1 - \lambda)\{2\alpha^2(1 - 2\delta) + [(4\delta - \alpha^2(1 - 2\delta))b]\}\}}{2h(1 + b)}, \\ P_R^{MR} &= \frac{a[\alpha^2(1 - 2\delta) + 4\delta + 4(1 - \delta)b]}{2h(1 + b)}, \end{aligned}$$

$$\begin{aligned}
 P_P^{\text{MR}} &= \frac{a}{2h(1+b)} \{6(1-\delta) + 3\alpha^2[(2\delta-1)(1-\lambda)] + b[4\delta + \alpha^2(4\delta + 3\lambda - 6\delta\lambda - 2) + 2(\delta-1)b]b\}, \\
 \pi_{\text{MR}}^{\text{MR}} &= \frac{a^2}{4h(1+b)} \{2 - 4\delta + \delta^2(6-4\lambda) - \alpha^2(1-2\delta)^2(1-\lambda) + 2(1-\delta)[4\delta(1-\lambda) + (1-\delta-2\lambda+2\delta\lambda)b^2]\}, \\
 \pi_P^{\text{MR}} &= \frac{a^2}{4h^2(1+b)} \left\{ +b \left\{ (1-2\delta)^2 \{8\alpha^2\lambda + \alpha^4[1-(3-\lambda)\lambda]\} - 4 + 4\delta(8\lambda - 12\delta\lambda + 2 - \delta) + 4b(1-\delta) \begin{bmatrix} \delta + 4\lambda - 12\delta\lambda + \\ \alpha^2(+1 - 2\delta - 3\lambda + 6\delta\lambda) \\ +(1-\delta-4\lambda+4\delta\lambda)b - 1 \end{bmatrix} \right\} \right\}, \tag{8}
 \end{aligned}$$

where  $h = \alpha^2[2\lambda + (2\lambda - 1)b - 3] + 4(1 - b)$

*Proof.* See Appendix D. □

**4.5. P and R Form the Coalition (Model PR).** In this model, P and R form a coalition. They collaborate and provide complementary services. The manufacturer as the leader of the model decides the wholesale price  $w$  and carbon reduction level  $s$ . Subsequently, coalition PR determines  $P_R^{\text{MR}}$  and  $P_P^{\text{MR}}$  simultaneously. In this case, the competition of price between the e-platform and retailer will be eliminated. Since PR will make joint decisions as a coalition, the commissions should be resolved. As the same, the coalition and manufacturer pursue the maximized profit. We formulated the profit function as follows:

$$\begin{aligned}
 \max \pi_M^{\text{MR}} &= w(Q_p + Q_r) - \frac{1}{2}s^2, \\
 \text{s.t. } \max \pi_{\text{PR}}^{\text{PR}} &= (P_R^{\text{PR}} - w)Q_r + (P_P^{\text{PR}} - w)Q_p. \tag{9}
 \end{aligned}$$

**Proposition 5.** Equation (9) has two formulas, and we obtain the results including the equilibrium wholesale price, retail price, and the optimal profit of channel as follows:  $w = a/4 - 2\alpha^2 - 4b$ ,  $s = \alpha\alpha/4 - 2\alpha^2 - 4b$ ,  $P_P^{\text{PR}} = 1/4[a - 2\alpha\delta/1 + b + 3a/2 - \alpha^2 - 2b]$ ,  $P_R^{\text{PR}} = 1/4a[2\delta - 1/1 + b + 3/2 - \alpha^2 - 2b]$ ,  $\pi_M^{\text{PR}} = a^2/8(2 - \alpha^2 - 2b)$ ,  $\pi_{\text{PR}}^{\text{PR}} = 1/16a^2[2 + 8(\delta - 1)\delta/1 + b + 2(1 - b)/(\alpha^2 + 2b - 2)^2]$ , where  $\alpha^2 + 2b < 2$ .

*Proof.* See Appendix E. □

### 5. Comparative Analysis of Results

Data from the China National Bureau of Statistics show that online retail sales of physical goods accounted for 24.9% of the total retail sales of consumer goods in 2020 (Sourced from National Bureau of Statistics of China). To keep the research issues' practicability, we control the consumer offline preference  $\delta = 0.75$  and investigate the performance of cooperation strategies and low-carbon level under different degrees of commission rate and channel competition.

**Proposition 6.** The performance of low-carbon level under different cooperative strategies are as follows.

(1)  $s^{\text{MP}} > s^{\text{MR}}$ , where  $0 < \alpha < 1$ ,  $0 < b < 1$  and  $0 < \lambda < 1$  are supported by  $0.125(11 - 4b) - 0.125\sqrt{105 - 8b + 16b^2} = \lambda_1 < \lambda < 1$ ;

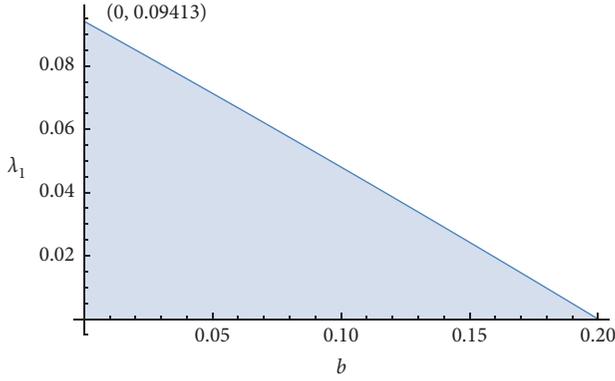
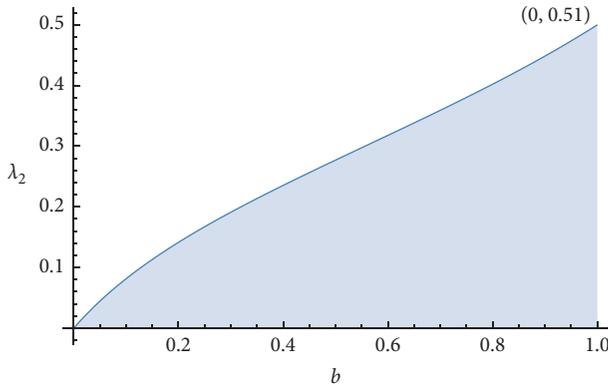
$s^{\text{MP}} < s^{\text{MR}}$ , where  $0 < \alpha < 1$ ,  $0 < b < 1$  and  $0 < \lambda < 1$  are supported by  $0 < b < 0.2$ ,  $0 < \lambda < \lambda_1 = 0.125(11 - 4b) - 0.125\sqrt{105 - 8b + 16b^2}$ ;

From Proposition 6 (1), we can find that the commission rate is closely related to the low-carbon level of the manufacturer. Moreover, from the angle of low-carbon performance, coalition MP is better than coalition MR in most cases. This can be explained that commission fees can help the manufacturer afford the cost of carbon reduction together under coalition MP. However, when the commission rate  $\lambda$  is too low to afford the carbon reduction costs, the coalition MR is the better choice from the perspective of a low-carbon level because the retailer owns a larger market share in real practice. Figure 2 shows us the range of  $\lambda_1$ . Moreover, we can see the maximum value of  $\lambda_1$  is very small.

(2)  $s^{\text{MR}} > s^{\text{RP}}$ , where  $0 < \lambda < 0.5$ ,  $0 < b < 1$ ,  $0 < \alpha < 1$ ;  $s_M^{\text{MR}} < s_M^{\text{RP}}$ , where  $0.5 < \lambda < 1$ ,  $0 < b < 1$ ,  $0 < \alpha < 1$ ; and  $s^{\text{MR}} > s^{\text{DC}}$ , where  $0 < \lambda < 1$ ,  $0 < b < 1$ ,  $0 < \alpha < 1$

**Proposition 6 (3)**  $s^{\text{DC}} > s^{\text{RP}}$ , where  $0 < \lambda < \lambda_2$ ;  $s_M^{\text{DC}} < s_M^{\text{RP}}$ , where  $\lambda_2 < \lambda < 1$

Proposition 6 (2) and Proposition 6 (3) demonstrated intuitively that when the commission rate is low, there is a relationship that  $s^{\text{MR}} > s^{\text{DC}} > s^{\text{RP}}$ . The lower the commission rate is, the less willing the e-platform is to participate in cooperation. Moreover, the low commission rate ( $0 < \lambda < \lambda_2$ ) makes the e-platform passively respond to low-carbon manufacturing and makes little contribution to it. Conversely, coalition RP has the highest level of carbon reduction when  $\lambda_2 < \lambda < 1$ , and the relationship that  $s^{\text{RP}} > s^{\text{MR}} > s_M^{\text{DC}}$  is formulated under this situation. It is worth mentioning that the commission rate has been offset in coalition RP, so we can get a conclusion that only the appropriate commission rate can promote carbon reduction of the manufacturer. Based on the insights of low-carbon, the e-platform always has the motivation to cooperate with others, but different commission rates make the e-platform prefer different coalition modes. From Figure 3, we can find the range of  $\lambda_2$ .

FIGURE 2: Range of  $\lambda_1$ .FIGURE 3: Range of  $\lambda_2$ .

Proposition 6 (4)  $s^{CC} > s^y$ ,  $y \in \{CD, MP, PR, MR\}$ , where  $0 < \lambda < 1$ ,  $0 < b < 1$ ,  $0 < \alpha < 1$ ;

From Proposition 6 (4), we can find that the centralized model can maximum carbon reduction. In the centralized model, all members share the cost and risk of carbon emission reduction, which alleviate manufacturer's pressure to reduce carbon emissions.

From Proposition 6 (1) to Proposition 6 (4), we can find that the commission rate determines which coalition the e-platform prefers to choose. At the same time, the manufacturer always tends to cooperate with others for bearing the costs and risks of low-carbon together.

*Proof.* See Appendix F.  $\square$

**Proposition 7.** From Proposition 7, we compare the retail price's size and analyze the impact of low-carbon preference of prices.

- (1)  $\partial P_p^y / \partial \alpha > 0$ ,  $\partial P_R^y / \partial \alpha > 0$ ,  $y \in \{CD, CC, MP, PR, MR\}$ ,  $\partial \omega^y / \partial \alpha > 0$ ,  $y \in \{CD, MP, PR, MR\}$ ,
- (2)  $P_p^y < P_R^y$ ,  $y \in \{CD, CC, MP, PR\}$ ,
- (3) In the MR model, the retail prices of two-channel satisfy the following relationships:  $P_p^{MR} < P_R^{MR}$ , if  $\alpha \in (0, \alpha_1)$ ;  $P_p^{MR} > P_R^{MR}$ , if  $\alpha \in (\alpha_1, \alpha_2)$ ,  $\lambda \in (\lambda_3, 1)$ .

(1) shows that both wholesale prices and retail prices increase with  $\alpha$  grows which is understandable. From a manufacturer's perspective, producing low-carbon products increases manufacturing costs. So, for maintaining profits, the manufacturer can only increase the wholesale price. After the manufacturer increases wholesale prices, the retailer and e-platform have naturally increased retail prices in response to low-carbon manufacturing.

(2) and (3) show that the retail price of traditional retailer is often higher than the price of the e-platform except for model MR. A common situation (CD, CC, MP, PR) is that  $R$  obtains a higher market share than e-platform because the retailer sells their low-carbon products in a dual channel while the e-platform merely sells products by its reselling business modes. To bridge these gaps of sales, the weak one such as e-platform have to lower their retail price to attract more consumers. However, it is quite different in model MR. With the increase of consumers' low-carbon preference and commission rate, the demand of products and e-platform's revenue is continuously growing. This is because retailer has made a great contribution to the e-platform's revenue. The e-platform does not worry about the gap of sales anymore, and then it raises retail prices for further profits. At this point, the retailer inevitably reduces their retail prices to limit the expansion of the e-platform's commission income. From the perspective of price comparison, we can find that when commission rate and consumer's low-carbon preference reach  $\lambda_3$  and  $\alpha_1$ , respectively, the e-platform prefers coalition MR than others to achieve more profits and attain power in LCDESC system. See the orange area in Figure 4 which is the range of  $\lambda_3$ .

*Proof.* See Appendix G.  $\square$

**Proposition 8.** From abovementioned propositions, we evaluate the performance of cooperative strategies under the perspective of pricing and low-carbon level. Moreover, in Proposition 8, we evaluate the performance from the angle of comparison between the partial coalition and noncooperation model.

(1)  $\pi_M^{PR} > \pi_M^{DC}$ , where  $0 < \alpha < 1$ , and  $\lambda \in (\lambda_4, 1)$ ;

$\pi_M^{PR} < \pi_M^{DC}$ , where  $0 < \alpha < 1$ , and  $\lambda \in (0, \lambda_4)$ ;

$\pi_{PR}^{PR} < \pi_P^{PR} + \pi_R^{PR}$ , in the blue area of Figures 5(b) to 5(d).

- (1) shows whether coalition RP is better than decentralized decision making depends on the channel competition. After many experiments, we finally find a rule that as cross-price sensitivity is growing, the blue area is decreasing. Excessive channel competition will lead to a low commission rate and malicious price cuts, and coalition PR can coordinate

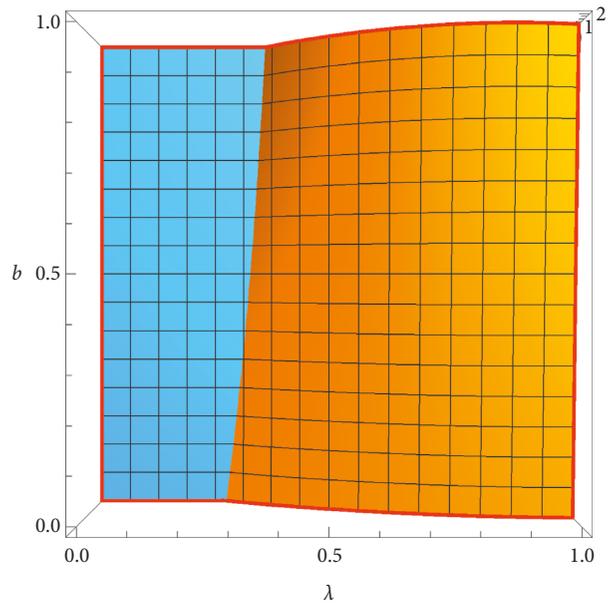
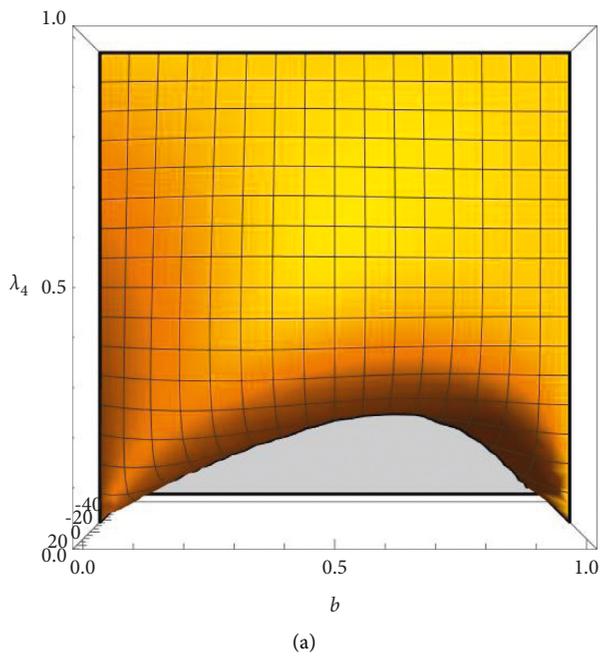
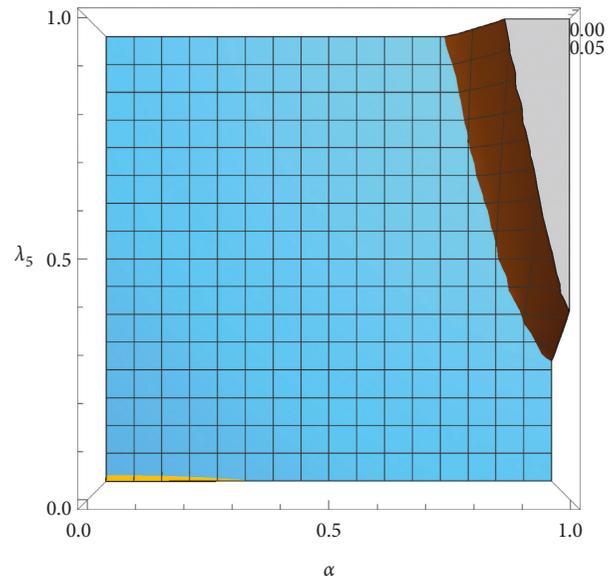


FIGURE 4: Range of  $\lambda_3$ .



(a)



(b)

FIGURE 5: Continued.

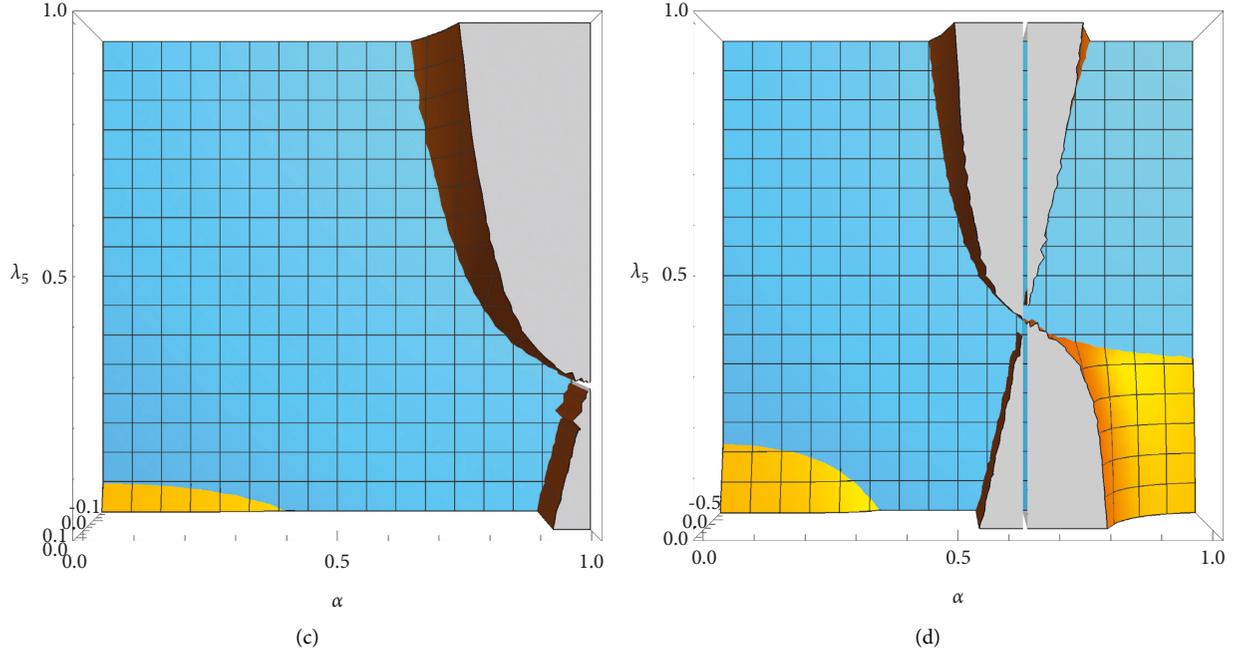


FIGURE 5: Range of  $\lambda_4$  and  $\lambda_5$ . (a) Range of  $\lambda_4$ . (b) Range of  $\lambda_5$  under  $b = 0.2$ . (c) Range of  $\lambda_5$  under  $b = 0.5$ . (d) Range of  $\lambda_5$  under  $b = 0.8$ .

high channel competition effectively. Besides, coalition RP has nothing to do with commission rate  $\lambda$ , but  $\lambda$  is still of great importance to model DC. In model DC, a high commission rate makes malicious price cuts and damages the interests of the supply chain system, while a too low commission rate is to promote further income of the LCDESC system. Instead, coalition RP is good news for the manufacturer; low channel competition allows manufacturer to increase wholesale price for reaping further benefits. So, coalition RP can reduce channel competition to improve the profits of the supply chain system. Figure 5 shows the range of  $\lambda_4$  and  $\lambda_5$ .

- (2)  $\pi_R^{MP} > \pi_R^{DC}$ , where  $0 < \alpha < 1$ , and  $0 < \lambda < 1, 0 < b < 1$ ;  
 $\pi_{MP}^{MP} > \pi_M^{MP} + \pi_P^{MP}$ , where  $\alpha > 0.6$ , and  
 $0 < \lambda < 1, 0 < b < 1$ ;  $\pi_{MP}^{MP} < \pi_M^{MP} + \pi_P^{MP}$ , where  $\alpha \leq 0.6$ ,  
and  $0 < \lambda < 1, 0 < b < 1$ .
- (3)  $\pi_P^{MR} > \pi_P^{DC}$ , where  $0 < \alpha < 1$ , and  $0 < \lambda < \lambda_6, b_1 < b < 1$ ;  
 $\pi_P^{MR} < \pi_P^{DC}$ , where  $0 < \alpha < 1$ , and  $\lambda_6 < \lambda < 1, 0 < b < b_1$ ;  
 $\pi_{MR}^{MR} > \pi_M^{MR} + \pi_R^{MR}$ , where  $0 < \alpha < 1$ , and  
 $0 < \lambda < 1, 0 < b < 1$ .

Based on Proposition 8 (2) and Proposition 8 (3), we can see that the manufacturer always has the motivation to cooperate with other members of supply chain. In coalition MP, as consumer low-carbon preference increases, the revenue of coalition MP is greater than the benefits of model DC. That is because the e-platform undertakes the partial low-carbon cost of the manufacturer under model MP and the coalition MP eliminates the double marginal effect between the manufacturer and e-platform. So, higher consumers' low-carbon preference means higher sales which is the motivation for the e-platform and manufacturer to cooperate with each other. Conversely, low

consumers' low-carbon preference and high-quality products cannot drive the sales growth of low-carbon products. It makes the e-platform support manufacturer negatively and cannot mobilize e-platform's enthusiasm to join the coalition. In model MR, the profit of the coalition is always greater than the profit of the decentralized model. Unlike coalition MP, the coalition MR has nothing to do with the value of the commission rate, and it just weakens the double marginal effect effectively. So, coalition MR is always beneficial to both the retailer and the manufacturer. Besides, the high commission rate and the low competition between channels ( $\lambda_6 < \lambda < 1, 0 < b < b_1$ ) make e-platform have stronger bargaining power. At this point, the coalition MR weakens the status of the e-platform and intensifies channel competition, which harms the profit of the e-platform.

*Proof.* See Appendix H.  $\square$

## 6. Numerical Simulation and LCDESC Coordination

Based on the abovementioned propositions, we can see that the low-carbon members of LCDESC always have the motivation to cooperate with others. However, the commission rate and cross-price sensitivity is an important factor for the preferences of cooperating strategies. For studying the effect of  $b$ ,  $\lambda$ , and  $\delta$  on pricing decisions and profit distribution more specifically, we first conduct a sensitivity analysis with numerical simulations for these key parameters or variables germane to formulate optimal pricing strategies and cooperation strategies, including pricing decisions, carbon emission reduction costs, as well as comparison of profits under different coalitions. Sensitivity analysis will allow us to better understand the changes in prices

and profit which are responses to changes of  $b$ ,  $\lambda$ , and  $\delta$ . Second, we introduce the cooperative game theory into this study to distribute the surplus profit. Then, we also use the numerical simulation to verify the applicability of the profit distribution mechanism as well. It should be noted that the value of the data in this paper is based on the assumptions and satisfies the theorems and the calculation conditions in the propositions.

**6.1. Decision Variables under Equilibrium.** To study the impact of consumers' low-carbon preference, channel preference, and commission rate on equilibrium results more deeply, we control the variables of the above parameters separately and study how each parameter affects the pricing problem of supply chain players under different value ranges.

**6.1.1. Impact of the Commission Rate  $\lambda$  on Pricing Decision.** Here, based on the survey of the e-platform's commission rate, we assume the commission rate increases from 0 to 1. Then, we drew Figure 6 by Mathematica to find the relationship between the price decision and commission rate under different coalitions:

Figure 6 clearly shows that as the commission rate of e-platform increases, the prices and low-carbon levels have a downward tendency under model DC. As e-platform's commission rate keeps increasing, the e-platform is in a stronger position, while the retailer is a weakened one in the game. Thus, e-platform can bear more low-carbon costs due to the additional income from commission fees. Reducing the retail price for higher income and sales volume is beneficial to e-platforms. Naturally, the retailer also follows this tendency to cut its retail price. Vicious competition of price has pushed back low-carbon manufacturer to cut prices to remedy products' sales and demand. In the long run, the interests of low-carbon manufacturer will be damaged, making them give up the manufacture of low-carbon products.

In the model MR, we find similar conclusions which are similar to the DC model. However, in the model MP, the situation is different. We find that as commission rate increase, dual-channel retail prices rise steadily, while wholesale prices are trending downturn. This phenomenon illustrates that when platforms cooperate with the manufacturer, all members of coalition shared the costs and income simultaneously. Therefore, when the e-platform occupies a stronger position, the high commission fee helps the manufacturer to afford the cost of low-carbon manufacturing. It will make the manufacturer willing to lower wholesale prices and increase carbon-reduction levels to increase product sales. For the retailer, the high commission fee means that the profit of their flagship stores on the e-platform is reduced, so the retailer has to increase the retail price to ensure the maximization of income under the same sales volume. Then, the e-platform's reselling channel also followed these trends and increased the retail price of low-carbon products. Thus, in model MP, the platform will be the final big winner. Besides, we also can say that cooperation is conducive to enhancing the market value of low-carbon products because all prices of members under coalition are higher than the decentralized model.

**6.1.2. Impact of the Cross-Price Sensitivity  $b$  on Pricing Decision.** Here, we set  $\lambda = 0.25$ ,  $\delta = 0.75$ ,  $\alpha = 0.5$  to describe the influence of cross-price sensitivity  $b$  on the changes in price decisions:

In this section, we can find it directly from Figure 7 that within a certain range ( $0 < b < 0.85$ ), as the cross-price sensitivity increases, all the prices and carbon emission reduction level increase accordingly. This is because when the cross-price sensitivity between channels is greater, the impact of price differences between channels on consumers' channel selection is greater. Moreover, it leads to competition between channels to be more intense, which encourages the manufacturer to increase the products' value of recognition and products' demands by improving the level of emission reduction. It also avoids vicious price cuts and plays a role in price protection.

From Figure 7, we also can see that when  $b > 0.5$ , the prices and low-carbon start to change rapidly. We roughly divide these changes into the following categories:

- (1)  $0.75 < b < 0.9$ ,  $P_R^{CC} > P_R^{MP} > P_R^{MR} > P_R^{RP} > P_R^{DC}$ ,  $P_P^{CC} > P_P^{MP} > P_P^{MR} > P_P^{RP} > P_P^{DC}$ ,  $w^{MP} > w^{MR} > w^{DC} > w^{RP}$ ,  $s^{CC} > s^{MP} > s^{MR} > s^{RP} > s^{DC}$ ;
- (2)  $0.64 < b < 0.75$ ,  $P_R^{CC} > P_R^{MP} > P_R^{RP} > P_R^{MR} > P_R^{DC}$ ,  $P_P^{CC} > P_P^{MP} > P_P^{MR} > P_P^{RP} > P_P^{DC}$ ,  $w^{MP} > w^{MR} > w^{RP} > w^{DC}$ ,  $s^{CC} > s^{MP} > s^{MR} > s^{RP} > s^{DC}$ ;
- (3)  $0.5 < b < 0.64$ ,  $P_R^{MP} > P_R^{CC} > P_R^{RP} > P_R^{MR} > P_R^{DC}$ ,  $P_P^{MR} > P_P^{RP} > P_P^{MP} > P_P^{DC}$ ,  $w^{MP} > w^{RP} > w^{MR} > w^{DC}$ ,  $s^{CC} > s^{MP} > s^{MR} > s^{RP} > s^{DC}$ ;

When  $b < 0.75$ , the coalition RP takes the manufacturer at a disadvantage. We can see from (1), the wholesale price of the model RP is lower than the wholesale price of the model DC. This is because the cooperation between the retailer and e-platform reduces the level of competition in the channel and puts the manufacturer at a disadvantage in bargaining. Although this method increases the profits of the platform and retailer, lowering the wholesale price has a negative impact on the performance of low carbon. Because the low-carbon level in model RP is still greater than the low-carbon level in the decentralized model at this time.

When cross-price sensitivity decreases, we can find that the prices of model RP begin to increase. It means that when the channel competition is not fierce, the coalition RP is more in line with the overall interests of SC. But as  $b$  is too low ( $b < 0.2$ ), the coalitions make little contribution. Therefore, we can conclude that the cooperation has alleviated the competition between the channels at the certain range of  $b$  ( $0.2 < b < 0.85$ ), and it plays a protective role in price competition. At the same time, when the channel competition is too intense, and the coalition RP undermines the manufacturer's determination to reduce carbon emissions.

**6.1.3. Impact of Consumer Offline Preference Coefficient  $\delta$  on Pricing Decision.** The continuous increase of online preference is the trend in the future. To study the impact of the increase of online preference, the influence of offline preference coefficients with different values on pricing decisions

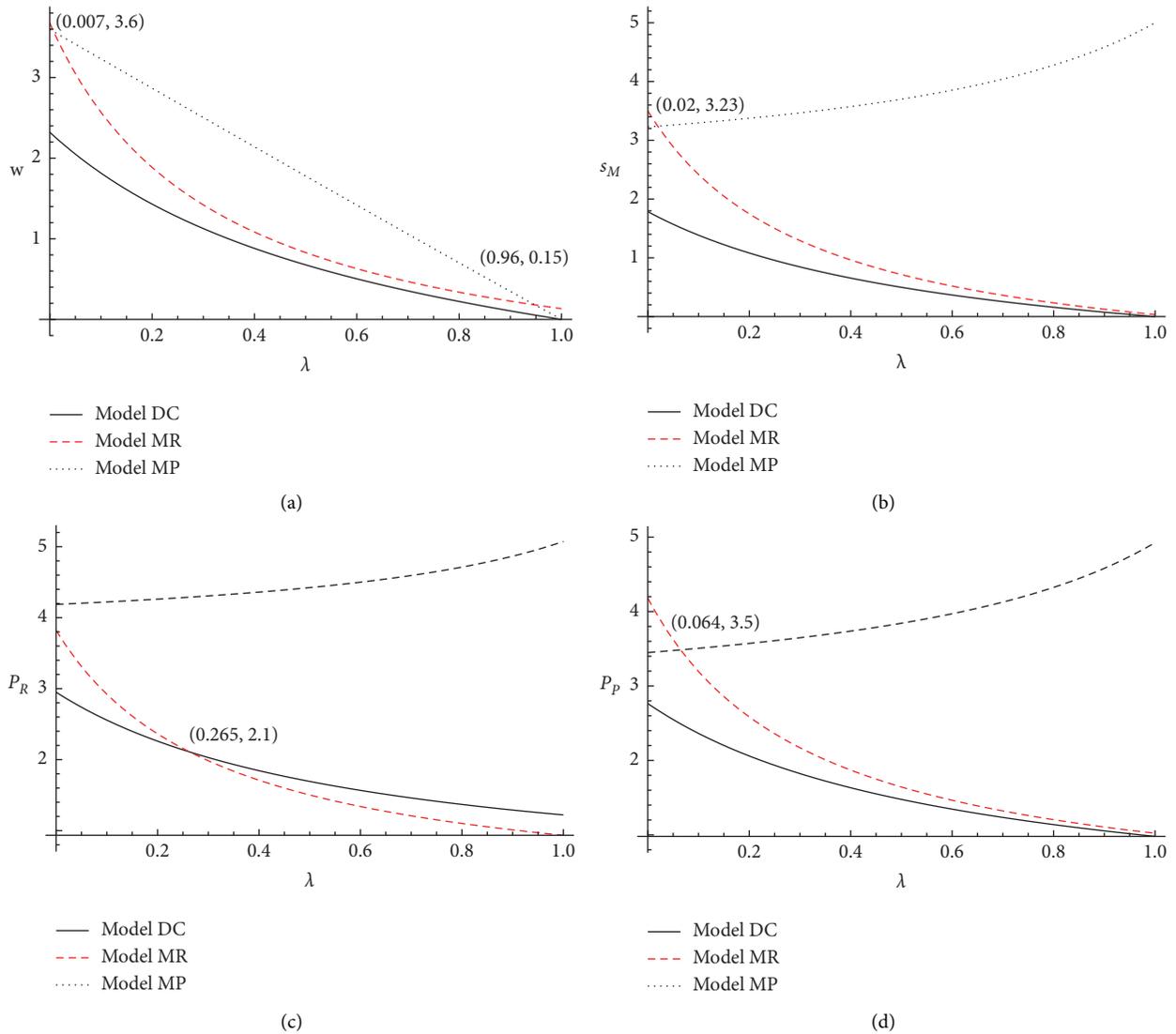


FIGURE 6: Impact of the commission rate on pricing decision. (a) Impact of the commission rate on wholesale price. (b) Impact of the commission rate on the low-carbon level. (c) Impact of the commission rate on the retail price of the retailer. (d) Impact of the commission rate on retail price of the e-platform.

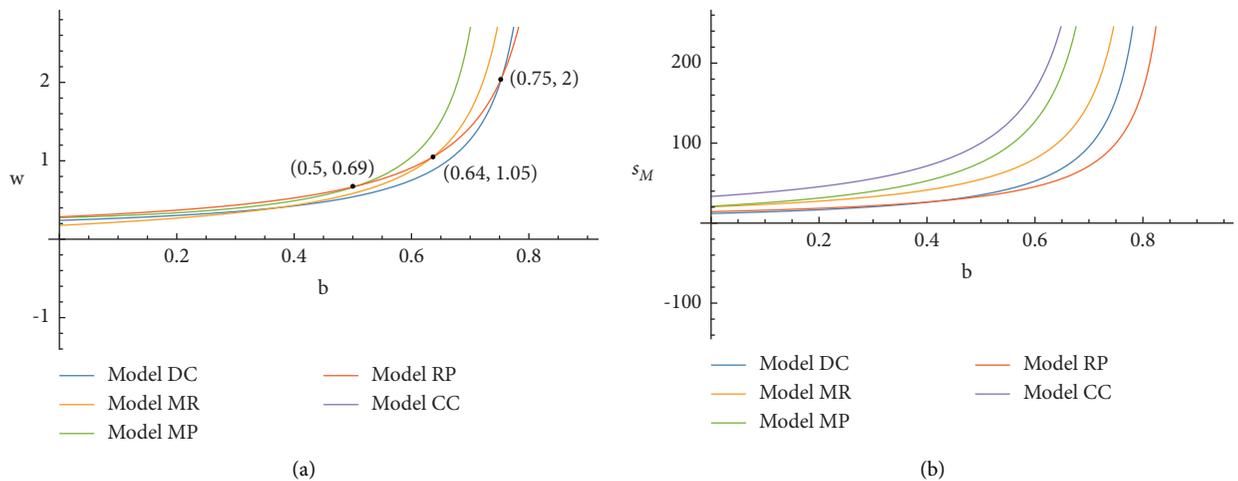


FIGURE 7: Continued.

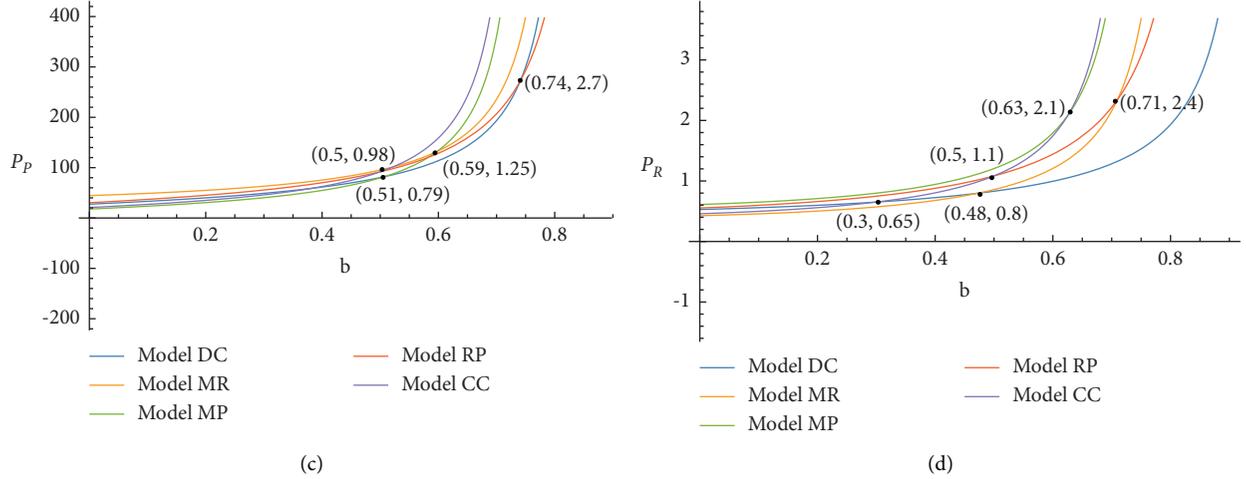


FIGURE 7: Impact of the cross-price sensitivity on pricing decision. (a) Impact of the cross-price sensitivity on wholesale price. (b) Impact of the cross-price sensitivity on a low-carbon level. (c) Impact of the cross-price sensitivity on retail price of the e-platform. (d) Impact of the cross-price sensitivity on retail price of the retailer.

is studied in this section, specifically, as shown in Figure 8 below.

From Figure 8, we can intuitively see that consumers' offline preferences mainly affect the retail prices and wholesale price and has little impact on the cost of carbon emission reduction. As consumers' offline preferences increase, retailer's price increases while the platform's retail price decreases. It is not difficult to understand that as consumers' loyalty to offline channels increases, retailer raise prices for further profit. At this time, the e-platform reduces the price to attract consumers for higher market sales.

Besides, specific value can be found as follows:

- (1) In model MP,  $\partial P_R^{MP}/\partial \delta = 0$ ,  $\partial P_P^{MP}/\partial \delta < 0$ ,  $\partial w/\partial \delta < 0$ , and  $P_P^{MP} < P_R^{MP}$ ;
- (2) In model MR,  $\partial P_R^{MR}/\partial \delta > 0$ ,  $\partial P_P^{MR}/\partial \delta < 0$ ,  $\partial w/\partial \delta < 0$ , and  $P_P^{MR} < P_R^{MR}$ , while  $\delta > 0.887$ ;
- (3) In model RP,  $\partial P_R^{RP}/\partial \delta > 0$ ,  $\partial P_P^{RP}/\partial \delta < 0$ ,  $\partial w/\partial \delta > 0$ , and  $P_P^{RP} < P_R^{RP}$ , while  $\delta > 0.49$ ;
- (4) In model DC,  $\partial P_R^{DC}/\partial \delta > 0$ ,  $\partial P_P^{DC}/\partial \delta < 0$ ,  $\partial w/\partial \delta > 0$ , and  $P_P^{DC} < P_R^{DC}$ , while  $\delta > 0.47$ ;
- (5) In model CC,  $\partial P_R^{CC}/\partial \delta > 0$ ,  $\partial P_P^{CC}/\partial \delta < 0$ , and  $P_P^{MR} < P_R^{MR}$ , while  $\delta > 0.5$
- (6)  $P_R^{CC} > P_R^{MP} > P_R^{RP} > P_R^{MR} \approx P_R^{DC}$ ,  $P_P^{CC} > P_P^{MP} > P_P^{MR} > P_P^{RP} > P_P^{DC}$ ,  $w^{MP} > w^{MR} > w^{RP} > w^{DC}$ ,  $s^{CC} > s^{MP} > s^{MR} > s^{DC} > s^{RP}$ .

We can get the conclusion from (6) that the grant coalition containing three members is the best choice for the whole supply chain system and carbon reduction. Conversely, model DC and coalition RP compromised carbon reduction of low-carbon manufacturers. Moreover, under coalition RP, the e-platform will lose the income of commission fees, which leads to retailer occupying a strong position. As the retailer's price rises, the manufacturer follows immediately and increases wholesale price slightly. Currently, the e-platform reduces the price for resisting the

high market share of the retailer, which causes e-platform fees unfair. So, coalition RP is not conducive to the long-term development of the cooperation.

Especially, the coalition MP is the best choice for e-platform only. That is because when consumer offline preference keeps dropping, the e-platform prefers to increase its retail price to obtain more income. So, the larger the critical value of  $\delta$ , the stronger the bargaining power of the platform. And in coalition MP, there is always  $P_P^{MR} > P_R^{MR}$ .

**6.2. Comparative Analysis of Total Profit under Different Models.** From the above numerical simulation of price decision making, we have concluded as follows: the excessively high cross-price sensitivity ( $b > 0.85$ ) and commission rate will make supply chain players maliciously reduce prices and disrupt the market order. For cooperation, we initially learned that cooperation is conducive to improve the quality of low-carbon products. On the other hand, it also alleviates channel competition and double marginal effects effectively. For further research on how cooperation can contribute to increased profitability, we set  $\delta = 0.75$  and  $a = 0.2$  to make the comparative analysis of total profit under different models.

**6.2.1. Influence of  $\delta$  on the Profit of the Whole Supply Chain.** We set  $\lambda = 0.4$ ,  $b = 0.67$ ,  $\alpha = 0.2$ ,  $a = 10$ , and then can obtain Figure 9 which describes the relationship between offline preference coefficient and supply chain profit.

From Figure 9, the relationship can be found as follows:

- (1)  $\delta < 0.257$ ,  $\pi_{SC}^{CC} \geq \pi_{SC}^{DC} > \pi_{SC}^{MR} > \pi_{SC}^{MP} > \pi_{SC}^{RP}$ ;
- (2)  $0.257 \leq \delta < 0.606$ ,  $\pi_{SC}^{CC} > \pi_{SC}^{MP} > \pi_{SC}^{MR} > \pi_{SC}^{DC} > \pi_{SC}^{RP}$ ;
- (3)  $\delta \geq 0.606$ ,  $\pi_{SC}^{CC} > \pi_{SC}^{MR} > \pi_{SC}^{MP} > \pi_{SC}^{DC} > \pi_{SC}^{RP}$ ;

We can see that the centralized decision-making model is always the optimal strategy that could obtain profit

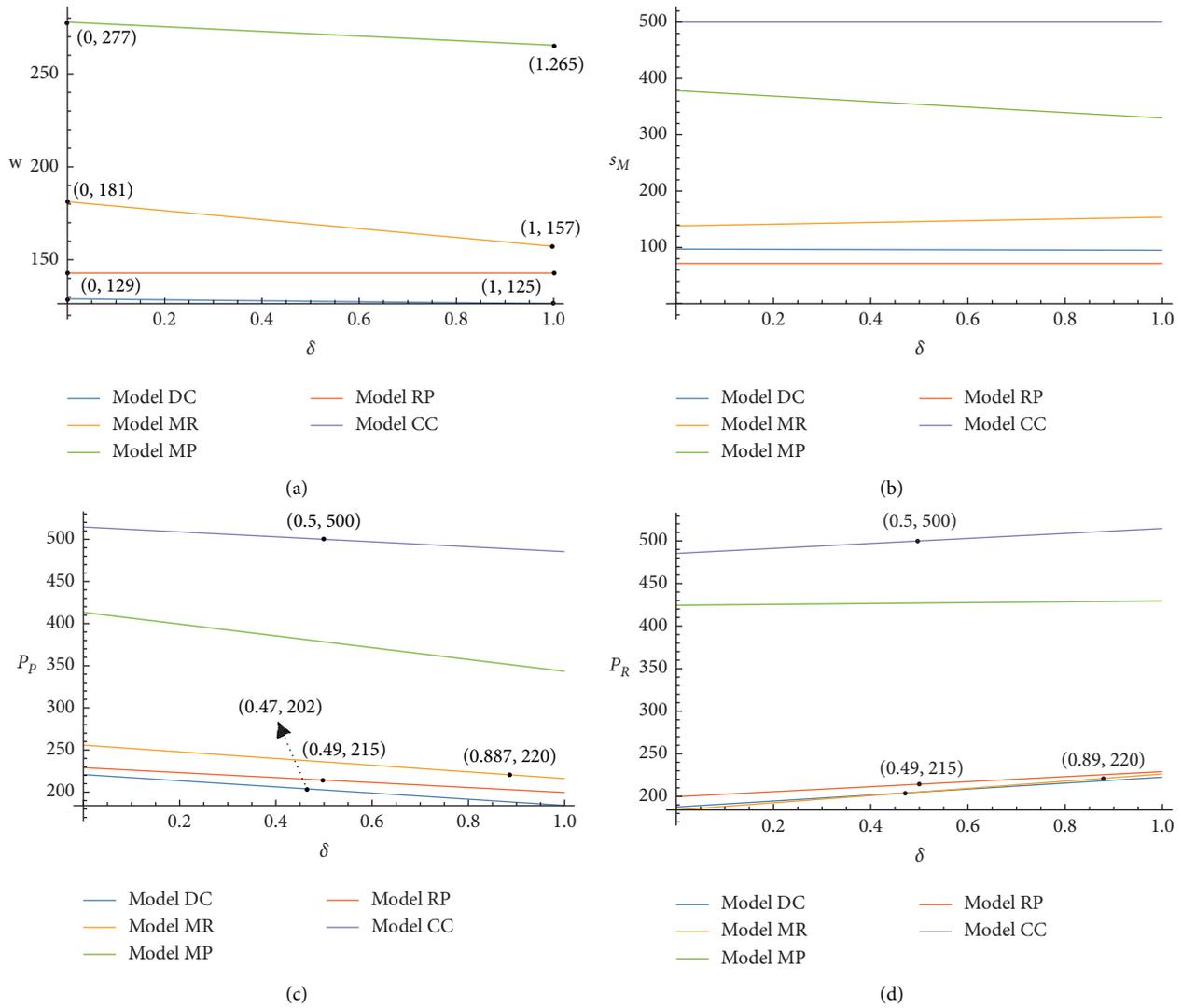


FIGURE 8: Impact of consumer offline preference coefficient on pricing decision. (a) Impact of consumer offline preference coefficient on wholesale price. (b) Impact of consumer offline preference coefficient on a low-carbon level. (c) Impact of consumer offline preference coefficient on retail price of the e-platform. (d) Impact of consumer offline preference coefficient on retail price of the retailer.

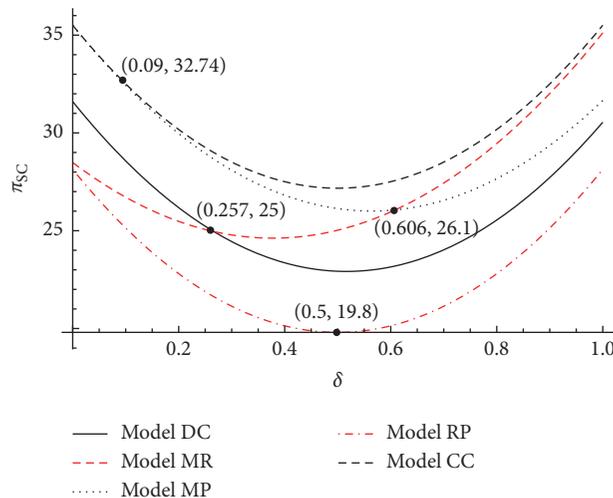


FIGURE 9: Impact of consumer offline preference on profit of whole LCDESC.

maximization. And when the consumer offline preference is low ( $\delta < 0.257$ ), the e-platform is reluctant to participate in cooperation. At this point, cooperation will damage the profits of e-platform, resulting in an overall decline in profits. Moreover, when the consumer offline preference is high ( $\delta \geq 0.257$ ), partnerships involving manufacturers are gaining ground ( $\pi_{SC}^{CC} > \pi_{SC}^{DC}; \pi_{SC}^{MP} > \pi_{SC}^{DC}; \pi_{SC}^{MR} > \pi_{SC}^{DC}$ ). That is because cooperation effectively reduces the impact of upstream and downstream double margins on the profitability of supply chain members. As the consumer offline preference is higher, the profit of coalition MR is greater. When the platform occupies a strong position ( $\lambda = 0.4$ ), the higher the market share of  $R$  ( $a_R = 0.606a$ ), the more the coalition MR will be able to compete with the power of the  $P$ . Besides,  $\pi_{SC}^{RP}$  is always lower than other models here. Moreover, we have already discussed it in Proposition 8 that there are strict conditions of cooperation successfully between  $P$  and  $R$ .

**6.2.2. Influence of  $\lambda$  on the Profit of the Whole Supply Chain.** We set  $\delta = 0.75, b = 0.67, \alpha = 0.2, a = 10$ , and then can obtain Figure 10 which describes the relationship between commission rate and supply chain profit.

From Figure 10, the relationship can be seen as follows:

- (1)  $\lambda < 0.073, \pi_{SC}^{CC} > \pi_{SC}^{MR} > \pi_{SC}^{DC} > \pi_{SC}^{MP} > \pi_{SC}^{RP}$ ;
- (2)  $0.073 \leq \lambda < 0.605, \pi_{SC}^{CC} > \pi_{SC}^{MR} > \pi_{SC}^{MP} > \pi_{SC}^{DC} > \pi_{SC}^{RP}$ ;
- (3)  $0.605 < \lambda \leq 0.95, \pi_{SC}^{CC} > \pi_{SC}^{MP} > \pi_{SC}^{MR} > \pi_{SC}^{DC} > \pi_{SC}^{RP}$ ;
- (4)  $0.95 < \lambda \leq 1, \pi_{SC}^{CC} \geq \pi_{SC}^{MP} > \pi_{SC}^{MR} > \pi_{SC}^{RP} > \pi_{SC}^{DC}$ ;

We have already reached the conclusion that the commission rate is the motivation for the manufacturer to cooperate with other members based on Proposition 8 and Figure 10. As the commission rate increases, the model MP follows the increase, while the model DC decreases sharply. And when  $\lambda > 0.605$ , the profit of model MP even exceeds the profit of model MR. That is because manufacturers profit from coalitions significantly. At this point, the increase in the manufacturer's profits encourages its enthusiasm to produce low-carbon products more. For the state of  $0.95 < \lambda$ , it is an extreme situation which seldom happens in real business. Therefore, we can conclude that centralized decision making is the best choice for the supply chain system, and the coalition RP harms the income of the whole supply chain.

**6.2.3. Influence of  $b$  on the Profit of the Whole Supply Chain.** We study the profit of the whole supply chain by setting  $\lambda = 0.4, \delta = 0.75, \alpha = 0.5, a = 10$ .

Figure 11 shows that as the cross-price sensitivity increase, the profits of the supply chain increase too. Moreover, there is a relationship that is:  $\pi_{SC}^{CC} > \pi_{SC}^{MR} > \pi_{SC}^{MP} > \pi_{SC}^{DC} > \pi_{SC}^{RP}$ . So, we can still observe that the greatest profit of the whole supply chain occurs in the centralized model. This is because cooperation effectively reduces the loss of profits caused by competition between channels. Therefore, we can obtain the conclusion from Figure 9 to Figure 11 that no matter how the variables change in the

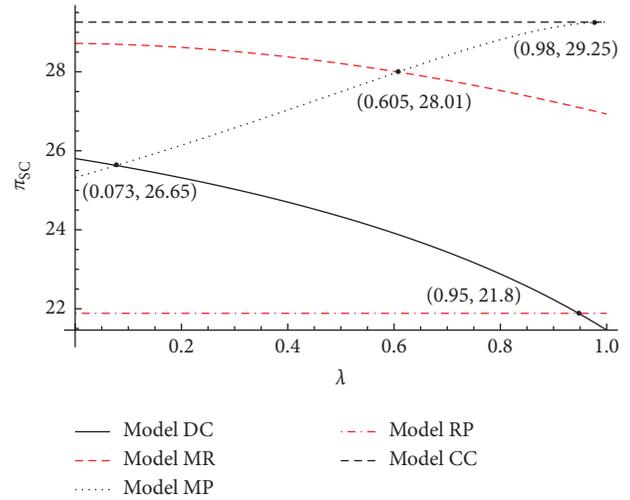


FIGURE 10: Impact of commission rate on profit of whole LCDESC.

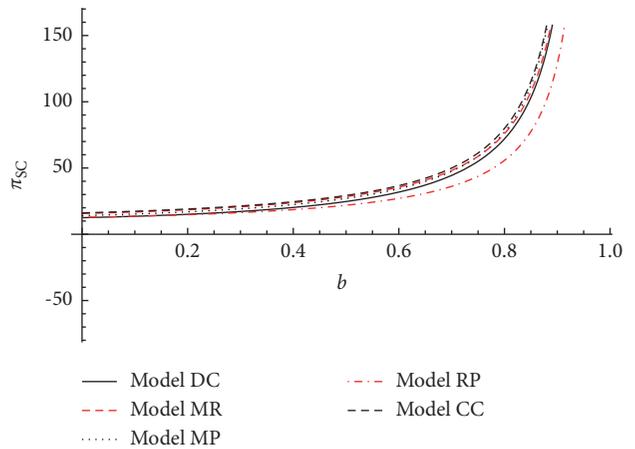


FIGURE 11: Impact of cross-price sensitivity on the profit of whole LCDESC.

model, the more supply chain players cooperate, and the higher profit of the supply chain can be obtained.

But one more important thing we have not discussed is how to distribute the surplus profit to the players of LCDESC. So, in the next part, we will resort it by a cooperative game theory.

**6.3. Comparison of Profit Distribution under Three Coordination Mechanisms.** Through the comparison of the profits, we found the grand coalition with the largest profit, and then we used the Shapley\CIS\Solidarity value in the cooperative game theory to find a reasonable profit distribution plan.

**6.3.1. Coordinating the LCDESC Based on Cooperative Game Theoretic.** In this section, we introduce the cooperative game theory to distribute the surplus profit of the grand coalition. There are some principles of reasonable distribution: First, the sum of the profits earned by all players must be equal to the supply chain profits in the centralized

model. Second, the final profit of players or coalitions should be greater than their characteristic value.

**6.3.2. Classical Cooperative Game Based on Characteristic Function Form.** Based on the cooperative game, we set the  $[N, v]$  to denote the characteristic function. Among them,  $N \in \{M, R, P\}$  denote three players of the LCDESC. Then, we calculate the characteristic value of all coalitions which includes the  $V(P)$ ,  $V(M)$ ,  $V(R)$ ,  $V(MP)$ ,  $V(MR)$ ,  $V(PR)$ , and  $V(MPR)$ . It is worth noting that the empty set is ignored here. According to the definition of the characteristic function, the characteristic value of a coalition is the minimum profit that it can obtain based only on its own contribution. To put it bluntly, the characteristic value is bargaining power's bottom line of the coalition and its players. For example, platform's profit in Models CD and PR are  $\pi_M^{DC}$  and  $\pi_M^{PR}$ . Then, from what we have said, it is obvious that the platform's characteristic value =  $\min\{\pi_M^{DC}, \pi_M^{PR}\}$ . The

same as  $V(P)$ , other characteristic values are obtained as shown in Table 5.

According to the calculation from propositions, we formulated the functions as follows:

$$\begin{aligned} v(M) &= \pi_M^{DC}; v(P) = \pi_P^{DC}; v(R) = \pi_R^{DC}; v(MP) = \pi_{MP}^{MP}; v(MR) \\ &= \pi_{MR}^{MR}; v(PR) = \pi_{PR}^{PR}; v(MPR) = \pi_{SC}^{CC}. \end{aligned} \quad (10)$$

**6.3.3. Sharply Value Mechanism.** Sharply value's contribution to the coordination of supply chain research has been common [38]. In this paper, we always use it to measure the average marginal contribution of the players. By applying SVM to our cooperative game  $[N, v]$ , and  $N = \{P, R, M\}$ , each player's Sharply value as:

$$\begin{aligned} W(|S|) &= \frac{((n-|S|)! (|S|-1)!)}{n!}, S \in \{CC, MP, MR, RP\}, \quad i = M \text{ or } P \text{ or } R, \\ x_i^{SVM} &= \sum_{i \in S, S \subset N} W(|S|) \left[ v(S) - v\left(\frac{S}{i}\right) \right], S \in \{CC, MP, MR, RP\}, \quad i = M \text{ or } P \text{ or } R, \end{aligned} \quad (11)$$

Where  $S$  denotes the coalitions and  $v(S/i)$  denotes the coalition's characteristic value except for the  $i$ .  $|S|$  denotes the number of players from coalition  $S$ , and  $W(|S|) = (n-|S|)! (|S|-1)!/n!$  is the weight factor.

**6.3.4. Solidarity Value Mechanism.** The solidarity value is the improvement value of the Sharpley value and between

the Sharpley value and the equal division value [39]. The solidarity value focuses on members' Solidarity and does not allow unproductive members to be eliminated in the coalition [30]. It not only considers the marginal contribution of the players but also makes the distributed profit as even as possible.

$$\begin{aligned} \psi_i(v) &= \sum_{i \in S, S \subset N} A^v(S) \frac{(n-|S|)! (|S|-1)!}{n!}, S \in \{CC, MP, MR, RP\}, \quad i = M \text{ or } P \text{ or } R, \\ A^v(S) &= \frac{1}{|S|} \left( \sum_{i \in S} \left[ v(S) - v\left(\frac{S}{i}\right) \right] \right), S \in \{CC, MP, MR, RP\}, \quad i = M \text{ or } P \text{ or } R. \end{aligned} \quad (12)$$

where  $S$  denotes the coalitions and  $v(S/i)$  denotes the coalition's characteristic value except for the  $i$ .  $A^v(S)$  is the weight parameter.  $|S|$  denotes the number of players from coalition  $S$ , and  $A^v(S) = 1/|S| \left( \sum_{i \in S} [v(S) - v(S/i)] \right)$  is the weight factor.

**6.3.5. CIS Value (the Center-of-Gravity of the Imputation-Set Value).** The center-of-gravity of the imputation-set value (CISV) considers the interests of individuals and coalitions at the same time, which assigns to player its profit first, and then distributes the surplus profit of grand coalition equally among players [40]. The expression for the CIS value is as follows:

$$CIS_i(v) = v(i) + \frac{1}{n} \left[ v(CC) - \sum_{i \in N} v(i) \right] \quad i = M \text{ or } P \text{ or } R, \quad (13)$$

$v(CC)$  is the characteristic value of model CC.

**6.4. Comparison of Profit Distribution under Three Coordination Mechanisms.** After introducing the cooperative game theory, we can obtain three new profit distributions. Whereas, only when the results meet individual rationality, it can coordinate the supply chain successfully. So, we first make a comparison between cooperative mechanisms and noncooperative mechanism under different degrees of

TABLE 5: Characteristic function value based on the cooperative game.

Coalition	(M)	(P)	(R)	(MP)	(MR)	(PR)	(MPR)
$v(s)$	$\pi_M^{DC}$	$\pi_P^{DC}$	$\pi_R^{DC}$	$\pi_{MP}^{MP}$	$\pi_{MR}^{MR}$	$\pi_{PR}^{PR}$	$\pi_{SC}^{CC}$

channel competition in 6.4.1. In Section 6.4.2, we make a comparison among different cooperative mechanisms under different degrees of commission rate and consumer offline preference. In Section 6.4.3, we make a comparison among different cooperative mechanisms under different degrees of channel competition. Finally, we make a comparison among mechanisms with the specific value of parameters.

6.4.1. *Comparison of the Profits of the Three Mechanisms under Different Cross-Price Sensitivities and Consumers' Offline Preference Coefficients.* We investigate these comparisons by setting  $\lambda = 0.25$ ,  $\delta = 0.75$ ,  $\alpha = 0.6$ ,  $b = 0.6$ ,  $a = 10$ , and analyze the impact of channel competition on comparison.

Figures 12 and 13 Intuitively show the distribution of each player under different profits distribution mechanisms and we use different linear colors to represent them.

Through the observation of Figure 12 and Figure 13, we can see that the profit of each player under the redistribution mechanism (SVM\CIS\Solidarity value) is all greater than the profit distribution under the benchmark model (the decentralized model), and this result does not change with the change of  $\delta$  and  $b$ . In addition, Figure 12 and Figure 13 Also reflect that as long as it conforms to the range of  $b$  ( $b < 0.7$ ) in the equilibrium analysis, no matter how consumers' offline loyalty changes, SVM, CIS, and Solidarity value can fully coordinate LCDESC, and achieve the greatest profit under a centralized setting. Moreover, it can be clearly seen in Figure 12 and Figure 13 that the profitability of players can be improved with three profit distribution plans. Among the three profit distribution plans, the manufacturer can obtain the greatest profit in SVM, the value obtained by players is more even in CIS and in solidarity value, the value got the effect of all players is not as obvious as the first two.

6.4.2. *Comparison of the Profits of the Three Mechanisms under Different Commission Rates and Consumers' Offline Preference.* We investigate these comparisons by setting  $\alpha = 0.6$ ,  $b = 0.6$ ,  $a = 10$ , and analyze the impact of commission rate and consumers' offline preference on comparison.

In this section, we set  $\alpha = 0.6$ ,  $b = 0.6$ ,  $a = 10$  to graphically illustrate the impact of  $\delta$  and  $\lambda$  on profit distribution in above figures. These figures visually compare the profit allocation between each of the three coordination mechanisms, where the lines show the results for the coordination mechanisms.

Among them, the Sharpley value mechanism is a classic utilitarian solution, it distributes the profits according to the marginal contribution of players. From Figure 14, we can summarize the findings in two aspects. From the aspect of consumer's offline preference coefficient, we can observe

that consumer's offline preference coefficient makes little difference in profit distribution of manufacturer and platform. But it has changed for the retailer. When the consumer's offline preference increases, the retailer's profits become greater. From the aspect of commission rate, it has different effects on the three profit distribution methods. For the manufacturer, as the commission rate increases, the manufacturer's profits first decrease and then increase. For retailers, as the platform commission rate increases, the retailer profits increase. For e-commerce platforms, as the commission rate increases, the profit distribution of e-commerce platforms decreased. This result is consistent with reality. In the transactions of supply chain players, when the retailer pays the commission fee as the basis of the transaction with the platform, its marginal contribution is further strengthened. So, when the commission rate increases, the retailer's profit in the alliance increases accordingly.

Under the CIS value which is shown in Figure 15, we can observe that consumers' offline preference has almost no effect on the profit distribution of manufacturers. For a retailer, when  $\lambda < 0.5$ , the influence of the  $\delta$  on the retailer's profit distribution is reduced. This is because the CIS value takes the disadvantaged groups into account, which reflects that CIS value maintains the orientation of win-win and sharing. For example, when offline retailers are at a disadvantage, consumers shift from offline to online buying products (i.e.,  $\delta < 0.5$ ), the central decisionmaker can use this egalitarian solution like CIS value to maintain the basic profitability of offline channels. It can not only reduce the risk of offline channels but also encourage offline retailers to join the cooperation.

Under the solidarity value which is shown in Figure 16, as  $\delta$  increases, profits of retailers and platforms first decrease and then increase, but the manufacturer is affected little. The solidarity value as the correction of Sharpley value, the solidarity value can supplement the weak part of the coalition to a certain extent, but the solidarity value magnifies the marginal contribution of members and distributes surplus profits equally.

6.4.3. *Influence of Consumers' Offline Preference and Cross-Price Sensitivity on the Distribution Mechanism Is as Follows.* We investigate these comparisons by setting  $\alpha = 0.25$ ,  $\lambda = 0.45$ ,  $a = 10$  and analyze the impact of channel competition on comparison.

In Figure 17, in the CIS value and solidarity value, we can observe that as the competition between channels intensifies, the profit of the supply chain increases, so that the profit distributed of players also increases. However, in the Sharpley mechanism, the trend of profit distribution among supply chain players is different. In the Sharpley value mechanism, the profit of the e-platform will decrease with the increase of  $b$ , which shows that when channel competition intensifies, retailers and e-platforms lose the initiative to cooperate, and then the e-platform loses its own advantages in the process too. It directly leads the e-platform to gradually reduce its own advantages, so that the profit of the e-platform is reduced due

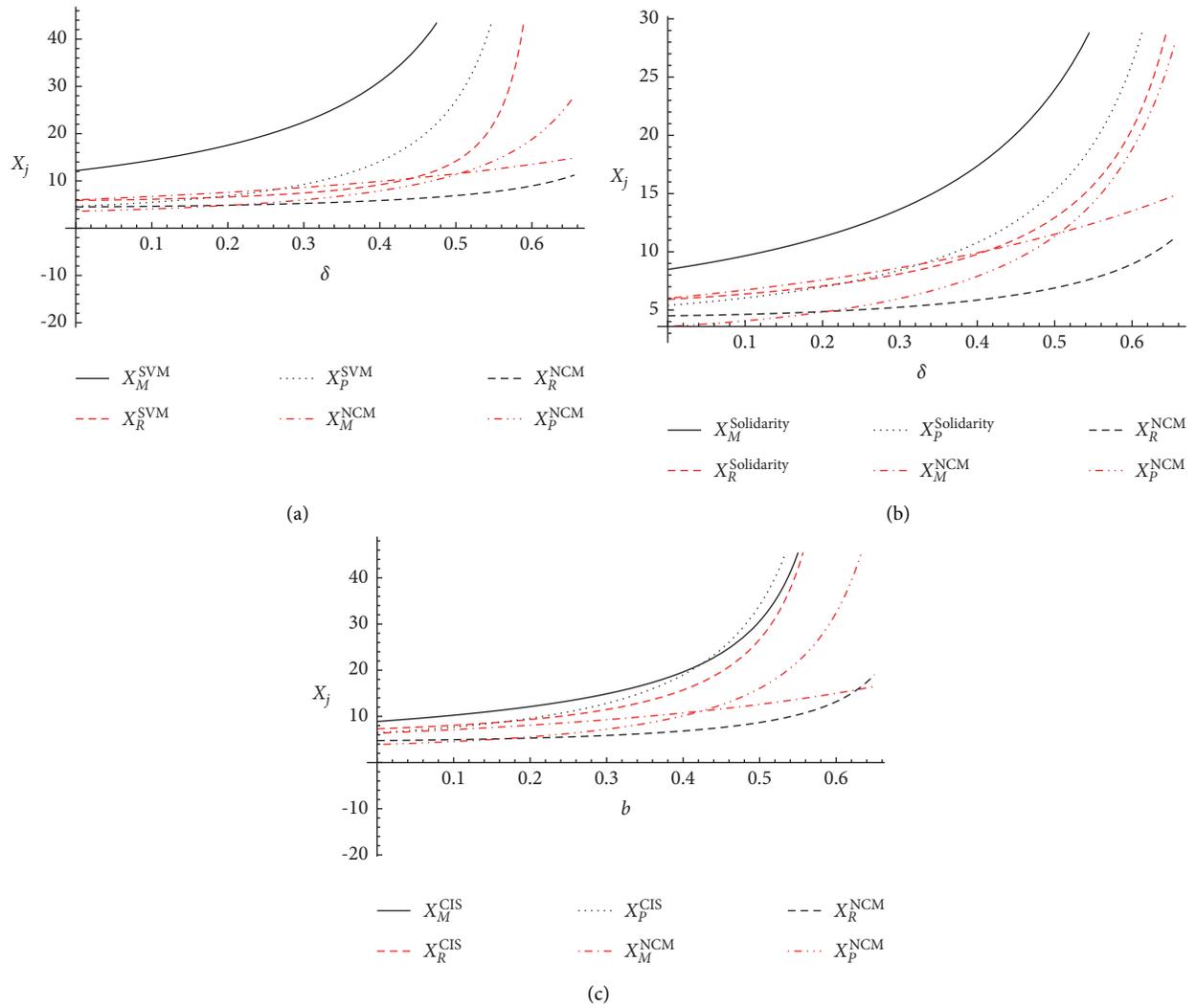


FIGURE 12: Comparison of the profits between model DC and SVM under different cross-price sensitivity. (a) Comparison of the profits between SVM and model DC. (b) Comparison of the profits between solidarity and model DC. (c) Comparison of the profits between CIS and model DC a b. c.

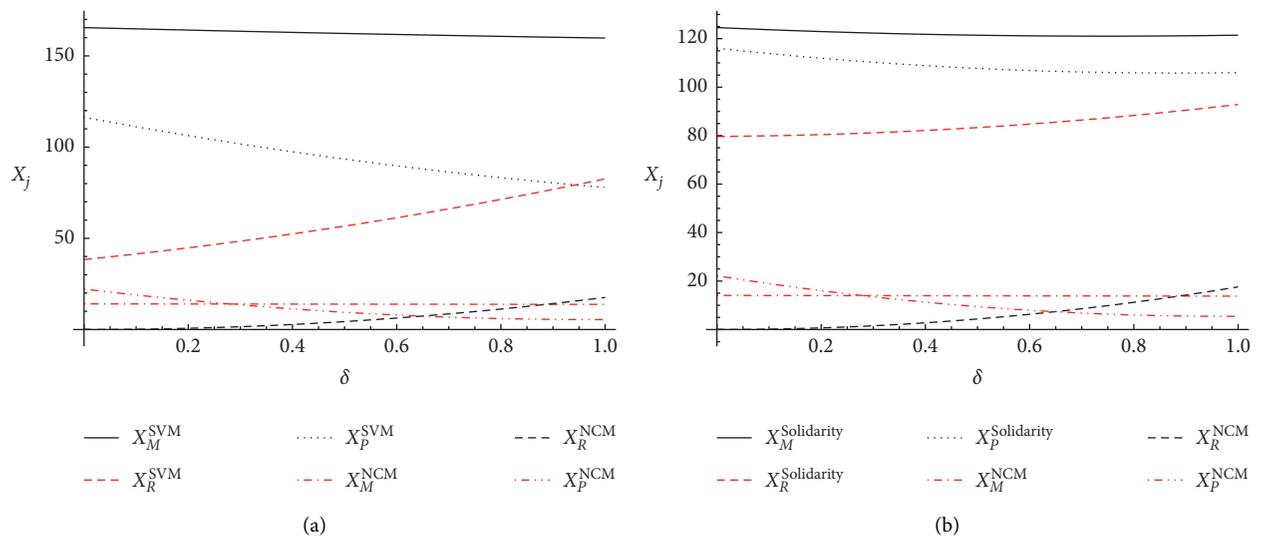


FIGURE 13: Continued.

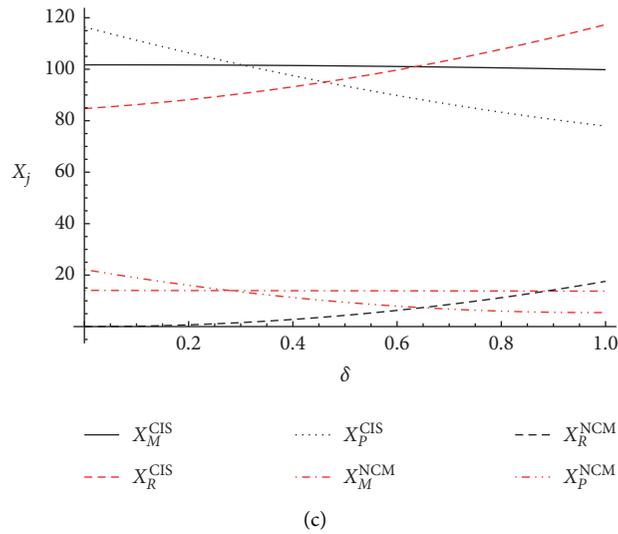


FIGURE 13: Comparison of the profits between model DC and SVM under different offline preference. (a) Comparison of the profits between SVM and model DC. (b) Comparison of the profits between solidarity and model DC. (c) Comparison of the profits between CIS and model DC.

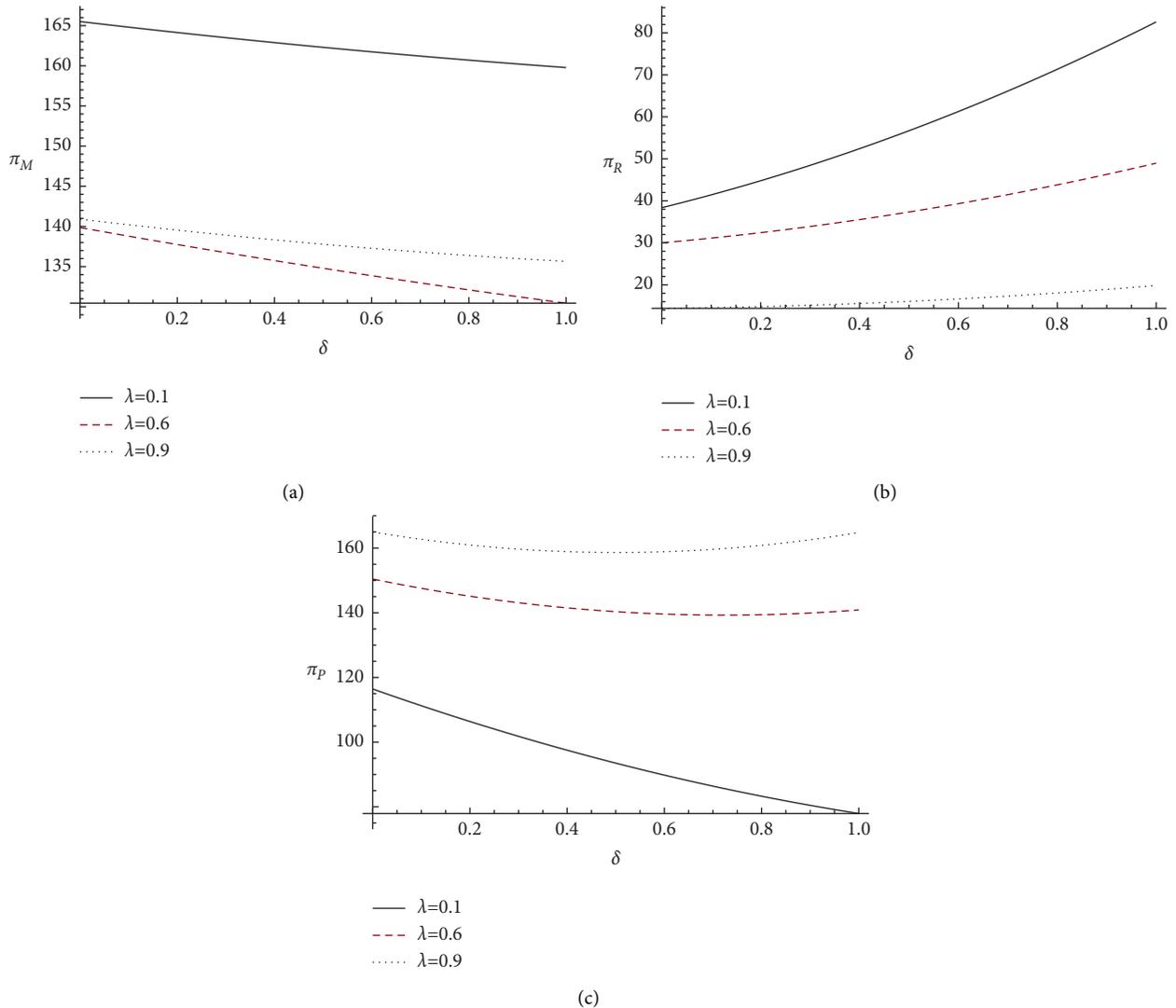


FIGURE 14: In SVM, comparison of the profits distribution of LCDESC under different commission rates and consumers' offline preference (a) manufacturer under SVM. (b) Retailer under SVM. (c) e-platform under SVM. a b. c.

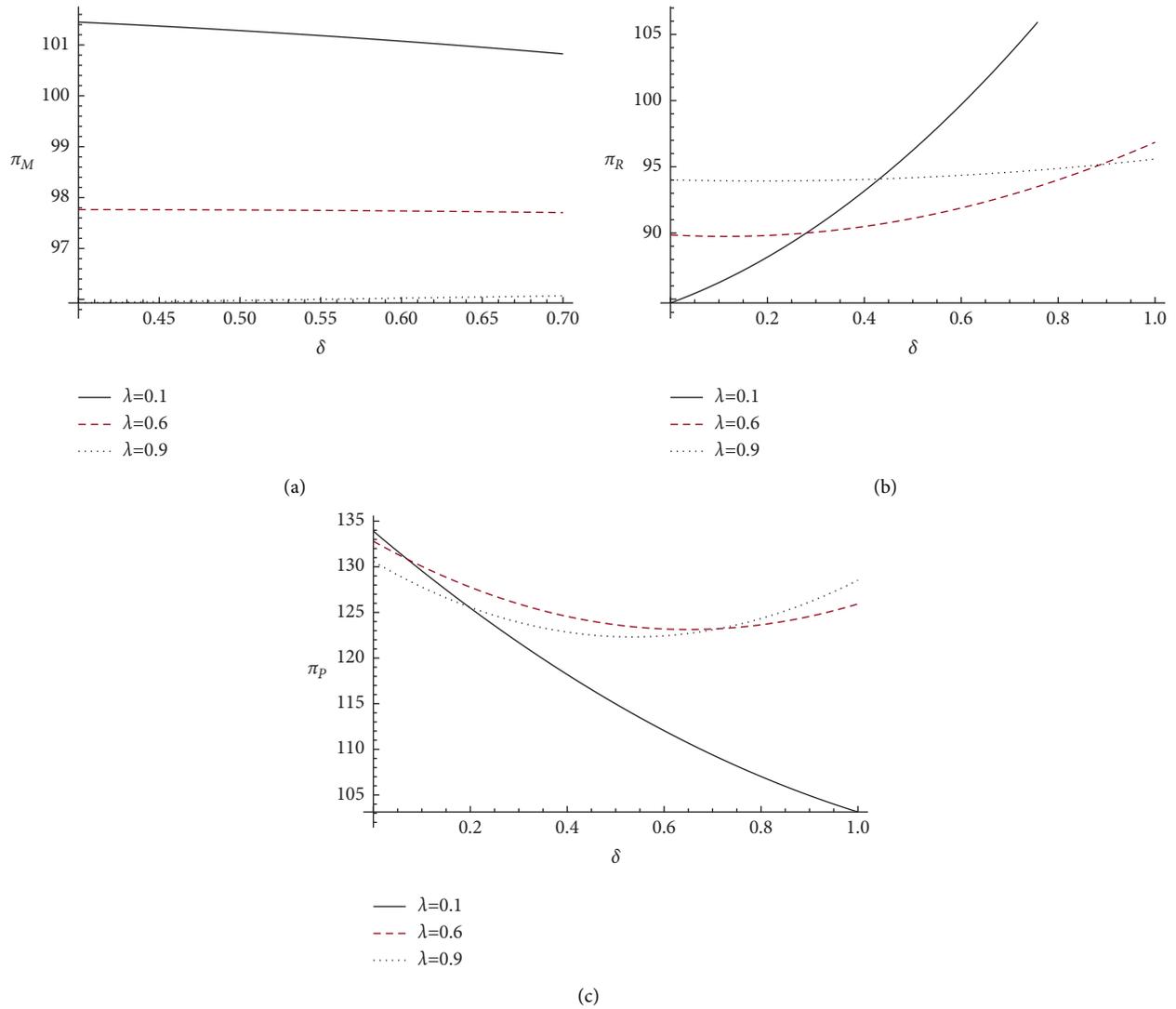


FIGURE 15: In CIS, comparison of the profits distribution of LCDESC under different commission rates and consumers' offline preference (a) manufacturer under CIS. (b) Retailer under CIS. (c) e-platform under CIS. a b. c.

to the reduction of its marginal contribution. In addition, combining with the above equilibrium analysis, when channel competition intensifies, manufacturers gradually get more power and occupy a dominant position, which will give them the strength and motivation to reduce carbon emissions, so that the demand for products is increased too. In this way, a virtuous circle is formed.

**6.4.4. Comparisons of Each Member's Average Shared Profits under the Different Mechanisms.** From above analyses, we set specific value of parameters  $\lambda = 0.3$ ,  $a = 10$ ,  $\alpha = 0.5$ ,  $\delta = 0.75$ ,  $b = 0.5$  and use Mathematica to obtain Figure 18:

In Figure 18, we can intuitively see the difference in profits of players under different distribution mechanisms. Under the Sharpley mechanism, the manufacturer is benefited from this most. Under the CIS value, the platform can be allocated the maximum profit. Under the solidarity value, the manufacturer can get the maximum

profit. Moreover, the profit distribution mechanism of the CIS value is more even than the Sharpley value. Thus, we can clearly see how to negotiate differently from different angles. For example, from the angle of the manufacturer, we should guide players to establish a profit distribution mechanism based on marginal contribution. So, it provides a scientific basis for the negotiation of profit distribution among players under different circumstances. In this process, we use it for further studies. Moreover, numerical simulation confirmed that these three distribution methods all satisfy individual rationality and collective rationality.

## 7. Discussion and Implications

**7.1. Discussion.** Based on the low-carbon dual-channel supply chain of the e-commerce platform composed of  $M$ ,  $P$ , and  $R$ , this paper answers the following three specific questions: 1. How to make pricing decisions for low-carbon

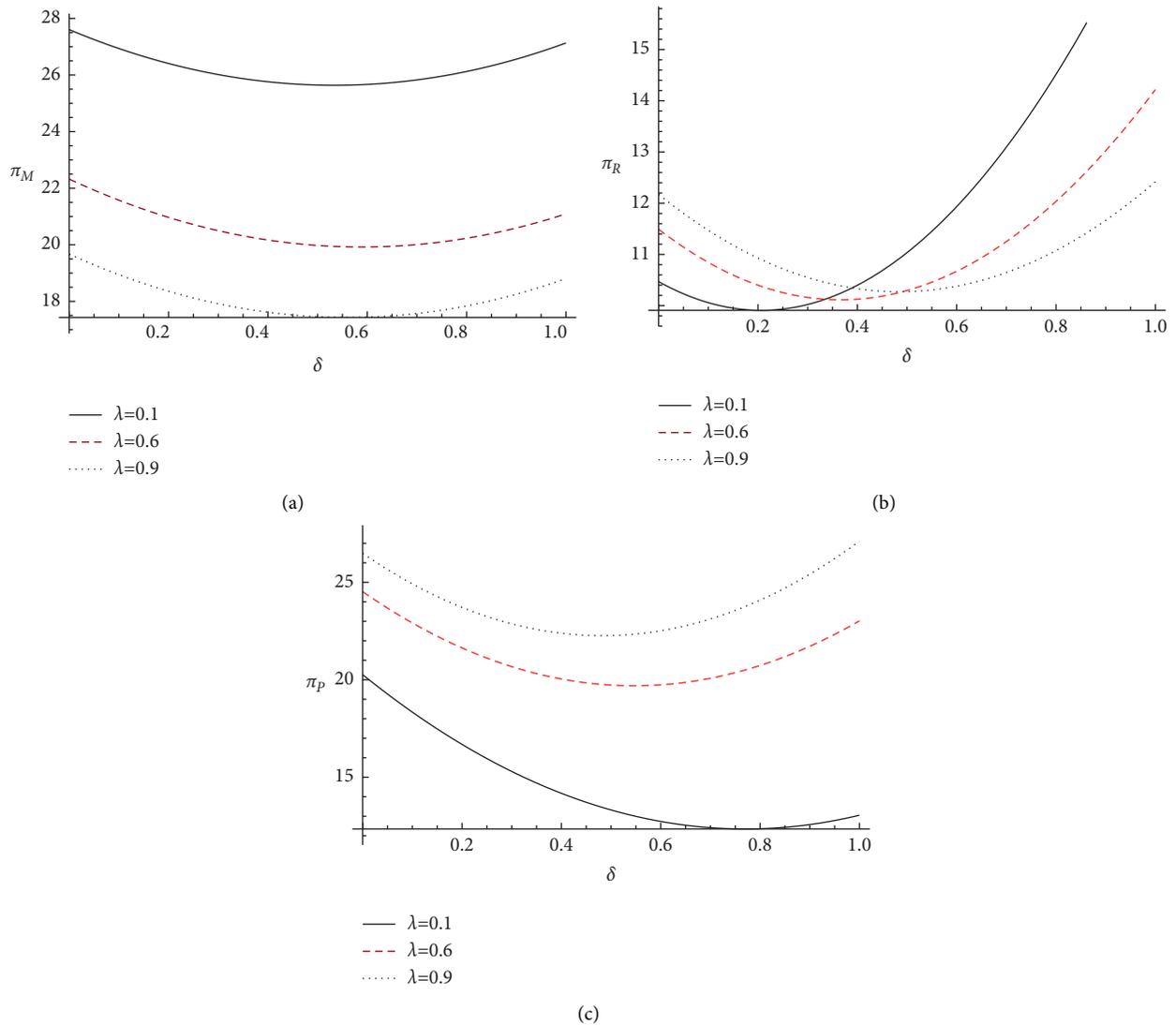


FIGURE 16: In Solidarity value (SV), comparison of the profits distribution of LCDESC under different commission rates and consumers' offline preference. (a) Manufacturer under SV. (b) Retailer under SV. (c) e-platform under SV.

products? 2. How do channel competition and commission rates affect LCDESC? 3. How should supply chain players cooperate?

For the issue of price decision, we discuss this issue based on the following background. Manufacturers' action of carbon emission reduction increases the cost of products, thereby increasing prices of the wholesale and retail. At this time, the value of the product is not the only competitive factor, the diversity of channels has become another important factor affecting product sales. And diversified channels have become a common choice for players, but their appearance has intensified the competition among players of the traditional dual-channel supply chain. In this context, we made an interesting discovery that the notion of low-carbon equaling high prices is not suitable for all situations. In this article, e-platforms not only sell products but they also charge a certain commission as a trading venue for retailers. Therefore, compared with traditional retailers,

e-platforms are more competitive. To obtain a greater market share, e-platforms often choose to reduce retail price; so, from this perspective, such finding breaks the traditional view to a certain extent.

To answer research question 2, too low commission rate and too high channel competition will damage the interests of the supply chain system and do harm to cooperation. Comparing with noncooperation (DC model), we found that cooperation (MR, MP, and CC) is always beneficial to the growth of supply chain benefits and helps to improve the low-carbon level of manufacturers. However, coalition RP is an exception. Coalition RP can only improve the low-carbon level of manufacturers but cannot effectively improve the profit of the coalition (model RP). Thus, cooperation (model RP) may not be a good choice for the coalition RP itself, but it contributes to manufacturer and consumer.

For research question 3, we find that profit distribution is the key issue affecting stability of cooperation based on

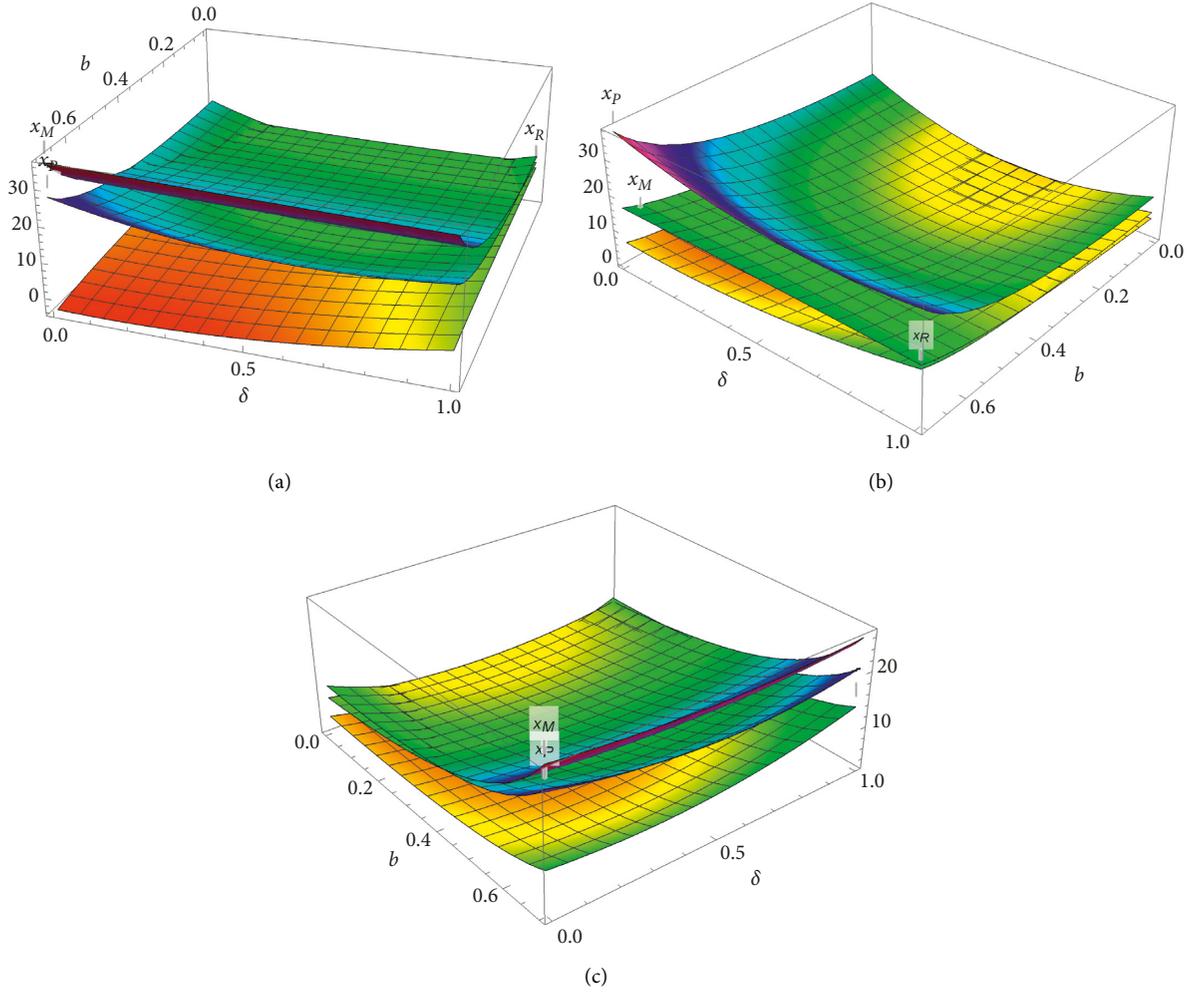


FIGURE 17: The effect of  $b$  and  $\delta$  on surplus profit distribution (a) In SVM. (b) In CIS. (c) In SV.

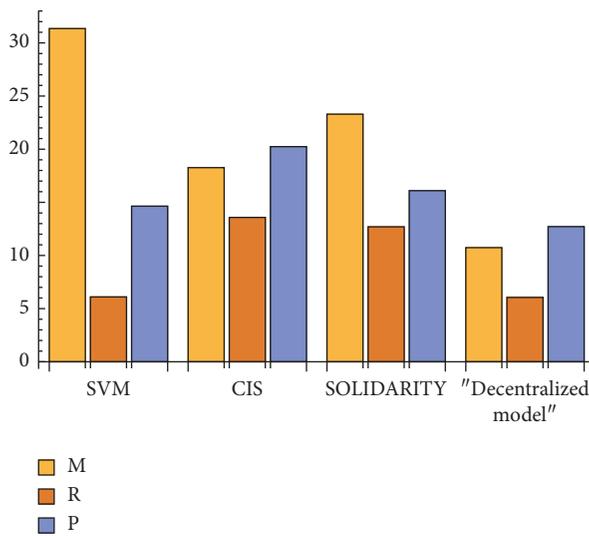


FIGURE 18: Comparison of surplus and profit shared by members.

previous studies [21, 22]. To address the issue of profit distribution for long-run cooperation, we set five models and perform equilibrium analysis: centralized (CC), decentralized (CD), and three partial coalition models (MR, MP, and PR). The equilibrium results show that the more cooperation among supply chain members, the greater the profit will be obtained. Three mechanisms (Shapley value, solidarity value, and CISV) are introduced to distribute the profit. Through comparison among these three mechanisms, we can find that  $M$  (manufacturer) gets the highest profit under the SVM, while  $P$  (e-platform) can maximize its profit under CIS. Besides, CIS is the fairest method in profit distribution, while SVM is the most unfair method. At this point, if the manufacturer insists to adopt marginal contribution mechanism as their profit distribution standards, the solidarity value is the better choice, which is fairer than SVM.

**7.2. Contributions and Practical Implications.** This paper provided theoretical and practical contributions for LCDESC are as follows:

This paper contributes to the literature in the following ways. First, the paper provides a brand-new perspective and studies the supply chain with channel competition under the cooperation framework. It also reveals that appropriate cooperative strategies can coordinate supply chain system. Second, the paper broke through the boundaries of traditional dual-channel and considered the role of e-platform in promoting low carbon. The involvement of e-platform improves consumers' recognition of low-carbon products and is conducive to the promotion of low-carbon products. Third, the paper introduced a cooperative game theory to LCDESC coordination, the results broaden the application scope of cooperative game theory and provides new methods for multiperson coordination problems.

This paper also has practical implications. This investigation provides strategies to the transformation of retailers and e-platforms. Strengthening the cooperation of supply chain members is the direction of future retailing reform. Through the mathematical model, we find that commission rate and channel competition degree are the key factors affecting cooperative strategies. The most important managerial implication and practical insight is "no perfect match, only match perfect." We cannot summarize the cooperation strategy into a simple combination among members but need to adjust in line with the degree of channel competition and commission rate. Besides, the appropriate cooperative strategy contributes to carbon emission reduction. In recent years, some e-platforms raise the commission rate blindly due to its great customer flow; this may render the other members to change their cooperative strategies, or even suspend cooperation. Therefore, partial concessions and egalitarianism may be the solution for the long-term cooperation.

## 8. Conclusions

The purpose of this research is to comprehend how to coordinate the e-commerce supply chain with channel

competition and double marginalization effect in a low-carbon environment. Through literature review, we develop the LCDESC structure and verify the impact of platform operation on low-carbon manufacturing. The conclusion can be found that appropriate cooperative strategies and profit distribution can contribute to the low-carbon level and supply chain coordination, which can be done by introducing noncooperative game and cooperative game theory. This article has contribution in many aspects. First, this study proves that proper cooperative strategies can effectively reduce the price of low-carbon products and improve the overall income of the supply chain system. Second, the commission rate and channel competition affect the cooperative strategies. Finally, the research expands the application scope of cooperative game theory and shows that cooperative game theory can successfully coordinate the three-player supply chain problem.

As with all research, there are some limitations and future research that should be noted. First, our findings are valid only under the low-carbon environment. However, more complex emission reduction policies and technologies have been introduced. Under the guidance of these policies, the retail industry is bound to change, i.e., how to cooperate better among retailers, manufacturers, and e-platforms that have become a new problem. To break inherent limitations, future research on optimal strategies for LCDESC under various carbon emission reduction policies and new technologies is worthy of investigation. Second, we research the issues that depend on the mathematical models, while empirical research has been widely used in research in the field of low carbon [41]. So, verifying the conclusion by empirical research will be the new direction of LCDESC. Third, supply chain finance has begun to be considered in supply chain management [42], and the platform will empower it by its own digital technology. So, how does the e-platform promote the supply chain finance may be the other research spot.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Supplementary Materials

Appendix A. Proof of Proposition 1. Appendix B. Proof of Proposition 2. Appendix C. Proof of Proposition 3. Appendix D. Proof of Proposition 4. Appendix E. Proof of Proposition 5. Appendix F. Proof of Proposition 6. Appendix G. Proof of Proposition 7. Appendix H. Proof of Proposition 8. (*Supplementary Materials*)

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