Research on Logistics Service Supply Chain Joint Carbon-emission Reduction Considering Consumers' Low-carbon Preference

Teng Li, Shuna Wang, and Zhenrui He

***Abstract*—This study investigates carbon-emission reduction decision-making for a two-echelon logistics service supply chain (LSSC) with a logistics service integrator (LSI) and a logistics service provider (LSP) considering consumers' low-carbon preferences. Four game models were comprehensively proposed to explore the influence of consumers' low-carbon preferences concerning the optimal solutions and profit of the LSSC. Subsequently, the optimal decisions are derived and numerical examples are drawn. The results show that the power structure significantly influences the level of carbon-emission reduction, outsourcing price, and the profit of LSSC system. Moreover, the profit margin and service price are complex influenced by all the power structure, and the preferences of consumers' low-carbon, and revenue retention. Additionally, we obtained two management insights. First, effective cooperation and appropriate competition can expand market demand, and improve the level of carbon-emission reduction, and maximize the LSSC profit. Second, in case of a Stackelberg game, a dominant power generates more profit.**

***Index Terms*—logistics service supply chain, carbon emission reduction, consumers'low-carbon preference, revenue sharing, game theory.**

I. Introduction

In different supply chain nodes, logistics and transportation are recognized as major contributors to environmental threats such as air pollution, global warming, and resource depletion [1, 2]. Green development has become a trend of economic development in the future [3]. In recent years, carbon emissions around the world have remained high. The Kyoto Protocol has raised awareness of the seriousness of carbon dioxide pollution in the transportation sector. Governments have increased their awareness of pollution emissions. To promote the sustainable development of the economy and society, China has already committed to peak carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060. It is imperative for the logistics service supply chain (LSSC) to implement carbon-emission reduction actions.

In recent years, the sustainability of logistics industry has become a research hotspot [4]. Block chain, big data, artificial intelligence and many other new technologies have been used to make LSSCs green and sustainable [5, 6]. Most third-party logistics (3PL) companies are now considered a sustainable supply chain approach to decreasing carbon emissions and delivery time [1].

As one of the largest emissions sources, LSPs play key roles in maintaining green and sustainable LSSC, and has received increasing attention. LSP's trust problem, operational efficiency, environmental sustainability, and low-carbon drivers usually explored by the DEA model and investigative method [7-11]. Since the outbreak of COVID-19, the pandemic has had a serious influence on the logistics industry and posed challenges to the LSPs. Risk management and resilience of LSP during the COVID-19 pandemic have attracted more attention [12-15]. Sustainable development goals are decisive components of the sustainability performance of an LSP [16]. LSIs also play an important role in the operations of supply chain. what's more, logistics integrator' behavior preference can affect the security and stability of LSSC [17]. Wang and Hu (2021) investigated the impact of risk preferences on the equilibrium decision of a green LSSC under fuzzy environments[2]. Government regulations, logistics service supply, and procurement also take a significant role in carbon-emission reduction and green development in the LSSC [4, 18].

At present, researchers mainly apply game theory to investigate LSSC decision. The impact of fairness concerns, loss-aversion preferences, risk attitude, and corporate social responsibility on quality defect guarantee decisions, service capacity procurement, quality control and coordination, and customer experience level in the LSSC were explored using game theory [2, 19-23]. With the rapid development of e-commerce, there are more and more studies on the intersection of e-commerce and LSSC from the perspective of game theory. Pricing decisions, logistics service choices, logistics services effort, and coordination in e-commerce were all investigated using a game model [24-27].

Existing game researches show well reference for decision-making of the LSSC in this study. Although many studies have investigated the LSSC, there is less research in carbon-emission reduction or consumer preference about LSSC from the perspective of the supply chain, as well as few studies from the perspective of all-sided power structures. Indeed, carbon-emission reduction is not widely researched in the current logistics service supply chain. In this paper, we explore the joint carbon-emission reduction decision-making for LSSC considering consumers' low-carbon preferences.

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We built four game models under different power structures and present numerical examples.

The remainder of this paper is as follows. The problems and assumptions of the models are outlined in section 2. Section 3 investigates four game models that consider consumers' low-carbon preferences under different power structures in the LSSC. Section 4 provides an equilibrium analysis. The numerical examples are shown in section 5. The last section presents the work conclusions in this study.

II. PROBLEM DESCRIPTIONS

It is assumed that only one LSI and one LSP in the two-stage LSSC. The LSP with a sense of green development outsource logistics services to the LSI at outsourcing price *w*. After that, the LSI integrate the logistics service quality of the LSP to provide them to customers at retail prices *p*. *c* is the cost for the logistics service of LSP.

Different power structures affect the decision-making power of supply chain participants. Eventually, the members make different profits. We developed four game models that considered various power structures. Subscript C, IS, PS, and VN, respectively represents the equilibrium value in the Centralized, LSI Stackelberg, LSP Stackelberg, and Vertical-Nash game model. And superscript I, P, and SC, respectively denotes LSI, LSP, and LSSC. To simplify the game model, the following basic assumptions were considered in this study.

Assumption 1. Following [28], [29], [30], and [31], the logistics service market demand *q* is complicatedly affected by the logistics service market scales, retail price, and the level of carbon-emission reduction:

$$q = B - \beta p + \gamma e \tag{1}$$

B is the market scale, β is the retail price elasticity of the logistics service. *p* is the service price, *e* is the carbon-emission reduction level of unit logistics service by LSP, γ is the coefficient of consumer' low-carbon preference. And the service price *p* equivalent to the outsourcing price *w* plus the profit margin *m*.

Assumption 2. To reduce carbon emission, the LSP should have more technological innovations in its logistics services. The investment cost of carbon-emission reduction for LSP is $\frac{1}{2}\bar{E}e^2$. $\bar{E}$ is the cost coefficient of carbon-emission reduction.

Assumption 3. To increase the incentive for LSP emission reduction, LSI shares revenue with LSP through revenue sharing contracts. LSI retains ϕ $(0 < \phi < 1)$ proportion of profits and then shares $(1-\phi)$ with LSP.

Assumption 4. To ensure that there are optimal solutions, it is assumed that $2\bar{E}\beta > \gamma^2$ and $B - c\beta > 0$.

Based on the problem description and assumptions above, we can obtain the profit expressions for the LSP, LSI, and LSSC, which are shown in Equation (2) to Equation (4):

The profit function for LSP is:

$$\pi^P = (w-c)\,q + (1-\phi)\,(p-w)\,q - \frac{1}{2}\bar{E}e^2 \tag{2}$$

The profit function for LSI is:

$$\pi^I = \phi\ (p-w)\,q \tag{3}$$

The overall profit function for LSSC is:

$$\pi^{SC} = (p-c)\,q - \frac{1}{2}\bar{E}e^2 \tag{4}$$

III. THE MODEL BUILDING

Four game models for the LSSC considering consumers' low-carbon preference to examine the impact of decision power will be established in this section.

A. Centralized Game Model(C)

In the centralized game model, the LSI and the LSP make decisions as a whole to maximize the overall profits of LSSC. The centralized game model can be obtained as follows:

$$max[\pi^{SC}(p,e)] = (p-c)\,(B-\beta p+\gamma e) - \frac{1}{2}\bar{E}e^2 \tag{5}$$

Theorem 1: In the centralized game model, if $\bar{E}\beta > \gamma^2$ and $B > c\beta$, the optimal solutions of the LSSC system are

$e_C^* = \frac{\gamma(B-c\beta)}{2\bar{E}\beta-\gamma^2}$,

$p_C^* = \frac{c\left(\bar{E}\beta-\gamma^2\right)+B\bar{E}}{2\bar{E}\beta-\gamma^2}$,

$q_C^* = \frac{\bar{E}\beta(B-c\beta)}{2\bar{E}\beta-\gamma^2}$.

Subsequently, the optimal profit of the LSSC is

$\pi_C^{SC*} = \frac{\bar{E}(B-c\beta\ )^2}{4\bar{E}\beta-2\gamma^2}$.

Proof. We can obtain the first-order condition of π^{SC} with respect to *e* and *p* by Equation (4). When $\bar{E}\beta > \gamma^2$, we can obtain $H = \begin{vmatrix} -2\beta & \gamma \\ \gamma & -\bar{E} \end{vmatrix} > 0$. It is a fact that the Hesse matrix of π^{SC} is negative definite. Hence, π^{SC} is the joint concave function of *e* and *p*. Therefore, the unique optimal solutions can be obtain by solving $\frac{\partial \pi^{SC}}{\partial p} = 0$ and $\frac{\partial \pi^{SC}}{\partial e} = 0$. The optimal solutions p_C^* and e_C^* are shown in Proposition 1.

Combining p_C^* and e_C^* into Equations (1) and (4), we get the optimal demand q_C^* and overall profit $\pi_C^{SC^*}$ of the LSSC in centralized game model.

B. IS Game Model

In the IS (Logistics Service Integrator Stackelberg) game model, the LSI is the leader, and the LSP acts as the follower. Firstly, the LSI determines the profit margin considering the reaction function of the LSP. Secondly, the LSP sets the wholesale price and the carbon-emission reduction level so as to maximize his profit.

Because *p* = *m* + *w*, we can get the profit function of the LSP and the LSI as follows.

$$\pi^P = [(w-c)+(1-\phi)\,m][B-\beta(m+w)+\gamma e] - \frac{1}{2}\bar{E}e^2 \tag{6}$$

$$\pi^I = \phi m[B-\beta(m+w)+\gamma e] \tag{7}$$

Thus, the LSI game model can be obtained as follows:

$$\max\ \pi^I(m) = \phi m\left[B - \beta\left(m + w\right) + \gamma e\right]$$
$$s.t. \begin{cases} w, \theta = argmax(\pi^P) \\ \max \pi^P(w, e) \\ = [(w-c) + (1-\phi)\, m][B - \beta(m+w) + \gamma e] \\ -\frac{1}{2}\bar{E}e^2 \end{cases} \quad (8)$$

Theorem 2: In the IS game model, if $2\bar{E}\beta > \gamma^2$ and $B > c\beta$, the optimal solutions of the LSI and LSP are as follows.

$$e^*_{IS} = \frac{\gamma\ (B-c\beta\ )}{2\left(\ 2\bar{E}\beta-\gamma^2\right)},$$

$$p^*_{IS} = \frac{\bar{E}\beta(3B+c\beta)-\gamma^2(B+c\beta)}{2\beta\left(\ 2\bar{E}\beta\ -\gamma^2\right)},$$

$$q^*_{IS} = \frac{\bar{E}\beta(B-c\beta)}{2\left(\ 2\bar{E}\beta-\gamma^2\right)},$$

$$w^*_{IS} = \frac{\bar{E}\beta[c\beta(2+\phi)+B(3\phi-2)]-\gamma^2[c\beta(1+\phi)-B(1-\phi)]}{2\beta\left(2\bar{E}\beta-\gamma^2\right)\phi}.$$

The optimal profit of the LSSC system are as follows.

$$\pi^{P*}_{IS} = \frac{\bar{E}\ (B-c\beta)^2}{8(2\bar{E}\beta-\gamma^2)},$$

$$\pi^{I*}_{IS} = \frac{\bar{E}\ (B-c\beta)^2}{4(2\bar{E}\beta-\gamma^2)},$$

$$\pi^{SC*}_{IS} = \frac{3\bar{E}\ (B-c\beta)^2}{8(2\bar{E}\beta-\gamma^2)}.$$

Proof. An optimal solution was obtained using the backward induction method. From Equation (6), the unique optimal reaction function solution for the LSP can be obtained. By combining the optimal reaction functions in Equation (7), we obtain m^*_{IS} by solving $\frac{\partial \pi^I_{IS}}{\partial p} = 0$. Substituting m^*_{IS} into the optimal reaction functions yields w^*_{IS} and e^*_{IS}.

Pluging m^*_{IS}, w^*_{IS} and e^*_{IS} into Equations (1)–(4), then considering $p = m + w$, we derives the optimal solutions q^*_{IS}, p^*_{IS}, π^{I*}_{IS}, π^{P*}_{IS} and π^{SC*}_{IS} in LSI Stackelberg game model.

C. PS Game Model

In the PS (Logistics Service Provider Stackelberg) game model, the LSP is the leader, and the LSI acts as the follower. Firstly, the LSP determines the wholesale price and the carbon-emission reduction level considering the reaction function of the LSI. Secondly, the LSI sets the profit margin so as to maximize his profit. The LSP game model can be obtained as follows:

$$\max \pi^I(m) = \phi m\left[B - \beta\left(m + w\right) + \gamma e\right]$$
$$s.t. \begin{cases} w, \theta = argmax(\pi^P) \\ \max \pi^P(w, e) \\ = [(w-c) + (1-\phi)\, m][B - \beta(m+w) + \gamma e] \\ -\frac{1}{2}\bar{E}e^2 \end{cases} \quad (9)$$

Theorem 3: In the LSP game model, if $2\bar{E}\beta > \gamma^2$ and $B > c\beta$, the optimal solutions of the LSI and LSP are as follows

$$e^*_{PS} = \frac{\gamma(B-c\beta\ )}{2\bar{E}\beta(1+\phi)-\gamma^2},$$

$$p^*_{PS} = \frac{c\left(\bar{E}\beta-\gamma^2\right)+B\bar{E}(1+2\phi)}{2\bar{E}\beta(1+\phi)-\gamma^2},$$

$$w^*_{PS} = \frac{c\left(2\bar{E}\beta-\gamma^2\right)+2B\bar{E}\phi}{2\bar{E}\beta(1+\phi)-\gamma^2},$$

$$q^*_{PS} = \frac{\bar{E}\beta(B-c\beta)}{2\bar{E}\beta(1+\phi)-\gamma^2}.$$

The optimal profit of the LSSC system are as follows.

$$\pi^{P*}_{PS} = \frac{\bar{E}(B-c\beta\ )^2}{2(2\bar{E}\beta(1+\phi)-\gamma^2)},$$

$$\pi^{I*}_{PS} = \frac{\bar{E}^2\beta\phi(B-c\beta\ )^2}{\left(2\bar{E}\beta(1+\phi)-\gamma^2\right)^2},$$

$$\pi^{SC*}_{PS} = \frac{\bar{E}(B-c\beta\ )^2(2\bar{E}\beta(1+2\phi)-\gamma^2)}{2\left(2\bar{E}\beta(1+\phi)-\gamma^2\right)^2}.$$

Proof. An optimal solution was obtained using the backward induction method. From Equation (6), the unique optimal reaction function solution for the LSI can be obtained. By combining the optimal reaction functions in Equation (6), we obtain e^*_{PS} and w^*_{PS} by solving $\frac{\partial \pi^P_{PS}}{\partial w} = 0$ and $\frac{\partial \pi^P_{PS}}{\partial e} = 0$.

Substituting e^*_{PS} and w^*_{PS} into the optimal reaction functions yields m^*_{PS}.

Pluging m^*_{PS}, w^*_{PS} and e^*_{PS} into Equations (1)–(4), then considering $p = m + w$, we derives the optimal solutions q^*_{PS}, p^*_{PS}, π^{I*}_{PS}, π^{P*}_{PS} and π^{SC*}_{PS} in LSP Stackelberg game model.

D. VN Game Model

In the VN (Vertical-Nash) game model, both the LSP and LSI simultaneously make decisions to optimize their own profits. The VN game model can be obtained as follows:

$$\begin{cases} \max \pi^P(w, e) \\ = [(w-c) + (1-\phi)\, m][B\beta(m+w) + \gamma e] - \frac{1}{2}\bar{E}e^2 \\ \max \pi^I(m) = \phi m\left[B - \beta\left(m + w\right) + \gamma e\right] \end{cases} \quad (10)$$

Theorem 4: In VN game model, if $2\bar{E}\beta > \gamma^2$ and $B > c\beta$, the optimal solutions of the LSI and LSP are as follows:

$$e^*_{VN} = \frac{\gamma(B-c\beta)}{2\bar{E}\beta\left(1+\frac{1}{2}\phi\right)-\gamma^2},$$

$$p^*_{VN} = \frac{c\left(\bar{E}\beta-\gamma^2\right)+B\bar{E}(1+\phi)}{2\bar{E}\beta\left(1+\frac{1}{2}\phi\right)-\gamma^2},$$

$$w^*_{VN} = \frac{c\left(2\bar{E}\beta-\gamma^2\right)+B\bar{E}\phi}{2\bar{E}\beta\left(1+\frac{1}{2}\phi\right)-\gamma^2},$$

$$q^*_{VN} = \frac{\bar{E}\beta(B-c\beta)}{2\bar{E}\beta\left(1+\frac{1}{2}\phi\right)-\gamma^2}.$$

The optimal profit of the LSSC system are as follows.

$$\pi^{P*}_{VN} = \frac{\bar{E}\ (B-c\beta)^2(2\bar{E}\beta-\gamma^2)}{2\left(2\bar{E}\beta\left(1+\frac{1}{2}\phi\right)-\gamma^2\right)^2},$$

$$\pi^{I*}_{VN} = \frac{\bar{E}^2\beta\phi(B-c\beta\ )^2}{\left(2\bar{E}\beta(1+\phi)-\gamma^2\right)^2},$$

$\pi_{VN}^{SC*} = \frac{\bar{E}(B-c\beta\ )^2(2\bar{E}\beta(1+2\phi)-\gamma^2)}{2\left(2\bar{E}\beta(1+\phi)-\gamma^2\right)^2}$.

Proof. First, we can obtain the first-order condition of π_{VN}^P with respect to (*w*, *e*) and the first-order derivatives of π_{VN}^I with respect to *m* from Equation (6) and Equation (7). Then, we can prove that the Hesse matrix of π_{VN}^P and π_{VN}^I are all negative definite. Hence, π_{VN}^P is the joint concave function in *(w, e)*, and π_{VN}^I is concave in m.

Second, the unique optimal solution of LSI and LSP can be obtained by solving $\frac{\partial \pi_{VN}^P}{\partial w} = 0$, $\frac{\partial \pi_{VN}^P}{\partial e} = 0$, and $\frac{\partial \pi_{VN}^P}{\partial m} = 0$, which gives e_{VN}^*, w_{VN}^*, and m_{VN}^* in Proposition 4.

Third, substituting the optimal solutions e_{VN}^*, w_{VN}^*, and m_{VN}^* into Equations(1)–(4), and $p = m + w$, we derives q_{VN}^*, p_{VN}^*, π_{VN}^{I*}, π_{VN}^{P*} and π_{VN}^{SC*} in VN game model.

IV. Model comparison

We get six corollaries by comparing the optimal solutions of four game models.

Corollary 1. The optimal carbon reduction level of the LSSC meets the conditions that

$$\begin{cases} e_C^* > e_{VN}^* > e_{PS}^* > e_{IS}^*,\ 0 < \gamma^2 < 2\bar{E}\beta(1-\phi) \\ e_C^* > e_{VN}^* \geq e_{IS}^* \geq e_{PS}^*,\ 2\bar{E}\beta(1-\phi) \leq \gamma^2 \leq 2\bar{E}\beta(1-\frac{1}{2}\phi) \\ e_C^* > e_{IS}^* > e_{VN}^* > e_{PS}^*,\ 2\bar{E}\beta\left(1-\frac{1}{2}\phi\right) \leq \gamma^2 \ \leq 2\bar{E}\beta \end{cases}$$

Proof. From the above propositions, we obtain the following.

$$e_C^* - e_{VN}^* = \frac{\bar{E}\beta(B-c\beta)\gamma\phi}{\left(2\bar{E}\beta-\gamma^2\right)\left(2\bar{E}\beta-\gamma^2+\bar{E}\beta\phi\right)},$$

$$e_{VN}^* - e_{PS}^* = \frac{\bar{E}\beta(B-c\beta)\gamma\phi}{\left(2\bar{E}\beta-\gamma^2+2\bar{E}\beta\phi\right)\left(2\bar{E}\beta-\gamma^2+\bar{E}\beta\phi\right)},$$

$$e_{IS}^* - e_{VN}^* = \frac{(B-c\beta)\gamma(\gamma^2-2\bar{E}\beta+\bar{E}\beta\phi)}{2(2\bar{E}\beta-\gamma^2)(-\gamma^2+\bar{E}\beta(2+\phi))},$$

$$e_{IS}^* - e_{PS}^* = \frac{(B-c\beta)\gamma(\gamma^2+2\bar{E}\beta(-1+\phi))}{2(2\bar{E}\beta-\gamma^2)(-\gamma^2+2\bar{E}\beta(1+\phi))},$$

$$e_C^* - e_{IS}^* = \frac{(B-c\beta)\gamma}{2(2a\beta-\gamma^2)}.$$

Based on the parametric assumption above, it is easy to verify that $e_C^* > e_{VN}^* > e_{PS}^*$ and $e_C^* > e_{IS}^*$.

When $0 < \gamma^2 < 2\bar{E}\beta(1-\phi)$, we have $e_{PS}^* > e_{IS}^*$.

When $2\bar{E}\beta(1-\phi) \leq \gamma^2 \leq 2\bar{E}\beta(1-\frac{1}{2}\phi)$, we have $e_{VN}^* > e_{IS}^*$ and $e_{IS}^* > e_{PS}^*$.

When $2\bar{E}\beta\left(1-\frac{1}{2}\phi\right) \leq \gamma^2 \leq 2\bar{E}\beta$, we have $e_{IS}^* > e_{VN}^*$.

Corollary 2. The optimal market demand of the LSSC meets the conditions that:

$$\begin{cases} q_C^* > q_{VN}^* > q_{PS}^* > q_{IS}^*, \\ 0 < \gamma^2 < 2\bar{E}\beta(1-\phi) \\ q_C^* > q_{VN}^* \geq q_{IS}^* \geq q_{PS}^*, \\ 2\bar{E}\beta(1-\phi) \leq \gamma^2 \leq 2\bar{E}\beta(1-\frac{1}{2}\phi) \\ q_C^* > q_{IS}^* > q_{VN}^* > q_{PS}^*, \\ 2\bar{E}\beta\left(1-\frac{1}{2}\phi\right) \leq \gamma^2 \ \leq 2\bar{E}\beta \end{cases}$$

Proof. From the above Propositions, we can obtain the following.

$$q_C^* - q_{VN}^* = -\frac{\bar{E}^2\beta^2(-B+c\beta)\phi}{(2\bar{E}\beta-\gamma^2)(-\gamma^2+\bar{E}\beta(2+\phi))},$$

$$q_{VN}^* - q_{PS}^* = \frac{\bar{E}\beta\phi(B-c\beta)}{(-\gamma^2+2\bar{E}\beta(1+\phi))(-\gamma^2+\bar{E}\beta(2+\phi))},$$

$$q_{VN}^* - q_{IS}^* = -\frac{\bar{E}\beta(B-c\beta)(\gamma^2+\bar{E}\beta(-2+\phi))}{2(2\bar{E}\beta-\gamma^2)(-\gamma^2+\bar{E}\beta(2+\phi))},$$

$$q_{VN}^* - q_{PS}^* = \frac{\bar{E}\beta(B-c\beta)(2\bar{E}\beta(\phi-1)-\gamma^2)}{2(2\bar{E}\beta-\gamma^2)(-\gamma^2+2\bar{E}\beta(1+\phi))},$$

$$q_C^* - q_{IS}^* = \frac{\bar{E}\beta(B-c\beta)}{2(2\bar{E}\beta-\gamma^2)}.$$

Based on parametric assumption above, it is easy to verify that $q_C^* > q_{VN}^* > q_{PS}^*$ and $q_C^* > q_{IS}^*$.

When $0 < \gamma^2 < 2\bar{E}\beta(1-\phi)$, $q_{PS}^* > q_{IS}^*$ and $q_{VN}^* > q_{PS}^*$, we have $q_C^* > q_{VN}^* > q_{PS}^* > q_{IS}^*$.

When $2\bar{E}\beta(1-\phi) \leq \gamma^2 \ \leq 2\bar{E}\beta(1-\frac{1}{2}\phi)$, $q_{VN}^* > q_{IS}^*$ and $q_{IS}^* > q_{PS}^*$, we have $q_C^* > q_{VN}^* \geq q_{IS}^* \geq q_{PS}^*$.

When $2\bar{E}\beta\left(1-\frac{1}{2}\phi\right) \leq \gamma^2 \leq 2\bar{E}\beta$, $q_{IS}^* > q_{VN}^*$ and $q_{VN}^* > q_{PS}^*$, we have $q_C^* > q_{IS}^* > q_{VN}^* > q_{PS}^*$.

Corollary 3. The optimal profit margin meets the conditions that

$$\begin{cases} m_{IS}^* \geq m_{VN}^* > m_{PS}^*, 0 < \gamma^2 \leq 2\bar{E}\beta(1-\frac{1}{2}\phi) \\ m_{VN}^* > m_{IS}^* > m_{PS}^*, \gamma^2 > 2\bar{E}\beta(1-\frac{1}{2}\phi) \end{cases}$$

Proof. From the above propositions, we can obtain the following

$$m_{IS}^* - m_{VN}^* = \frac{(B-c\beta)(\bar{E}\beta(2-\phi)-\gamma^2)}{2\beta\phi(\bar{E}\beta(2+\phi)-\gamma^2)},$$

$$m_{IS}^* - m_{PS}^* = \frac{(B-c\beta)(2\bar{E}\beta-\gamma^2)}{2\beta\phi(-\gamma^2+2\bar{E}\beta(1+\phi))} > 0,$$

$$m_{VN}^* - m_{PS}^* = \frac{\bar{E}^2\beta(B-c\beta)\phi}{(2\bar{E}\beta(1+\phi)-\gamma^2)(\bar{E}\beta(2+\phi)-\gamma^2)} > 0.$$

Based on parametric assumption above, it is easy to verify that $m_{IS}^* > m_{PS}^*, m_{VN}^* > m_{PS}^*$.

When $0 < \gamma^2 < 2\bar{E}\beta(1-\frac{1}{2}\phi)$, $m_{IS}^* - m_{VN}^* > 0$, we have $m_{IS}^* \geq m_{VN}^* > m_{PS}^*$.

When $\gamma^2 = 2\bar{E}\beta(1-\frac{1}{2}\phi)$, $m_{IS}^* - m_{VN}^* = 0$, we have $m_{IS}^* = m_{VN}^* > m_{PS}^*$.

When $\gamma^2 > 2\bar{E}\beta(1-\frac{1}{2}\phi)$, $m_{IS}^* - m_{VN}^* < 0$, we have $m_{VN}^* > m_{IS}^* > m_{PS}^*$.

Corollary 4. The optimal LSP profit meets the conditions that

$$\begin{cases} \pi_{PS}^{P*} > \pi_{VN}^{P*} > \pi_{IS}^{P*},\ 0 < \gamma^2 < 2\bar{E}\beta(1-\frac{1}{2}\phi) \\ \pi_{PS}^{P*} \geq \pi_{IS}^{P*} \geq \pi_{VN}^{P*},\ 2\bar{E}\beta(1-\frac{1}{2}\phi) \leq \gamma^2 \ \leq 2\bar{E}\beta(1-\frac{1}{3}\phi) \\ \pi_{IS}^{P*} > \pi_{PS}^{P*} > \pi_{VN}^{P*},\ 2\bar{E}\beta\left(1-\frac{1}{3}\phi\right) \leq \gamma^2 \ \leq 2\bar{E}\beta \end{cases}$$

Proof. From the above propositions, we obtain the following.

$$\pi_{PS}^{*}-\pi_{VN}^{*}=\frac{\bar{E}(B-c\beta)(\bar{E}\beta-\gamma^2)\phi}{(-\gamma^2+2\bar{E}\beta(1+\phi))(-\gamma^2+\bar{E}\beta(2+\phi))},$$

$$\pi_{PS}^{P*}-\pi_{IS}^{P*}=-\frac{\bar{E}(B-c\beta)^2(3\gamma^2+2\bar{E}\beta(-3+\phi))}{8(2\bar{E}\beta-\gamma^2)(-\gamma^2+2\bar{E}\beta(1+\phi))},$$

$$\pi_{VN}^{P*}-\pi_{IS}^{P*}=\frac{\bar{E}(B-c\beta)^2(3\gamma^4+2\bar{E}\beta\gamma^2(\phi-6)-\bar{E}^2\beta^2(4\phi+\phi^2-12))}{8(2\bar{E}\beta-\gamma^2)(\gamma^2-\bar{E}\beta(2+\phi))^2}.$$

Based on the parametric assumption above, it is easy to verify that $\pi_{PS}^{P*}>\pi_{VN}^{P*}$.

When $0<\gamma^2<2\bar{E}\beta(1-\frac{1}{2}\phi)$, $\pi_{VN}^{P*}-\pi_{IS}^{P*}>0$, we have $\pi_{PS}^{P*}>\pi_{VN}^{P*}>\pi_{IS}^{P*}$.

When $2\bar{E}\beta(1-\frac{1}{2}\phi)\leq\gamma^2\leq 2\bar{E}\beta(1-\frac{1}{3}\phi)$, $\pi_{VN}^{P*}-\pi_{IS}^{P*}<0$, and $\pi_{PS}^{P*}-\pi_{IS}^{P*}>0$, and so, we have $\pi_{PS}^{P*}\geq\pi_{IS}^{P*}\geq\pi_{VN}^{P*}$.

When $2\bar{E}\beta\left(1-\frac{1}{3}\phi\right)\leq\gamma^2\leq 2\bar{E}\beta$, $\pi_{PS}^{P*}-\pi_{IS}^{P*}<0$, we have $\pi_{IS}^{P*}>\pi_{PS}^{P*}>\pi_{VN}^{P*}$.

Corollary 5. The optimal LSI profit meets the conditions that

$\pi_{IS}^{I*}>\ \pi_{VN}^{I*}>\pi_{PS}^{I*}$

Proof. From the above propositions and assumptions, we obtain the following.

$$\pi_{IS}^{I*}-\pi_{VN}^{I*}=\frac{\bar{E}(B-c\beta)^2\left(\gamma^2+\bar{E}\beta(-2+\phi)\right)^2}{4\left(2\bar{E}\beta-\gamma^2\right)\left(\gamma^2-\bar{E}\beta(2+\phi)\right)^2}>0,$$

$$\pi_{VN}^{I*}-\pi_{PS}^{I*}=\frac{\bar{E}^3\beta^2(B-c\beta)^2\phi^2\left(-2\gamma^2+\bar{E}\beta(4+3\phi)\right)}{\left(\gamma^2-2\bar{E}\beta(1+\phi)\right)^2\left(\gamma^2-\bar{E}\beta(2+\phi)\right)^2}>0,$$

Thence, it is easy to verify that $\pi_{IS}^{I*}>\ \pi_{VN}^{I*}>\pi_{PS}^{I*}$.

Corollary 6. The optimal profit of the LSSC meets the conditions that:

$$\begin{cases}\pi_{C}^{SC*}>\pi_{VN}^{SC*}>\pi_{PS}^{SC*}>\pi_{IS}^{SC*},\\ 0<\gamma^2<2\bar{E}\beta(1-\phi)\\ \pi_{C}^{SC*}>\pi_{VN}^{SC*}>\pi_{IS}^{SC*}>\pi_{PS}^{SC*},\\ 2\bar{E}\beta(1-\phi)\leq\gamma^2\leq 2\bar{E}\beta(1-\frac{1}{2}\phi)\\ \pi_{C}^{SC*}>\pi_{IS}^{SC*}>\pi_{VN}^{SC*}>\pi_{PS}^{SC*},\\ 2\bar{E}\beta\left(1-\frac{1}{2}\phi\right)\leq\gamma^2\leq 2\bar{E}\beta\end{cases}$$

Proof. From the above propositions and assumptions, we get the following.

$$\pi_{C}^{SC*}-\pi_{IS}^{SC.*}=\frac{\bar{E}(B-c\beta)^2}{16a\beta-8\gamma^2},$$

$$\pi_{C}^{SC*}-\pi_{VN}^{SC.*}=\frac{\bar{E}(B-c\beta)^2\left(2\bar{E}\beta\gamma^2(2+\phi)-\gamma^4+\bar{E}^2\beta^2\left(4-4\phi+\phi^2\right)\right)}{2\left(2\bar{E}\beta-\gamma^2\right)\left(\gamma^2-\bar{E}\beta(2+\phi)\right)^2},$$

$$\pi_{VN}^{SC.*}-\pi_{PS}^{SC*}=\frac{\bar{E}(B-c\beta)^2}{2\left(\gamma^2-2\bar{E}\beta(1+\phi)\right)^2}\frac{6\bar{E}\beta\gamma^4(1+\phi)-\gamma^6+3\bar{E}^2\beta^2\gamma^2\left(4+8\phi+5\phi^2\right)+2\bar{E}^3\beta^3\left(4+12\phi+15\phi^2+6\phi^3\right)}{\left(\gamma^2-\bar{E}\beta(2+\phi)\right)^2},$$

$$\pi_{VN}^{SC.*}-\pi_{IS}^{SC*}=\frac{1}{8}\bar{E}(B-c\beta)^2\frac{5\gamma^4-10\bar{E}\beta\gamma^2(2+\phi)+\bar{E}^2\beta^2(20+20\phi-3\phi^2)}{(2\bar{E}\beta-\gamma^2)(\gamma^2-\bar{E}\beta(2+\phi))^2},$$

$$\pi_{IS}^{SC*}-\pi_{PS}^{SC*}=\frac{\bar{E}(B-c\beta)^2(-\gamma^4+4\bar{E}\beta\gamma^2(1+\phi)+4\bar{E}^2\beta^2(-1-2\phi+3\phi^2))}{8(2\bar{E}\beta-\gamma^2)(\gamma^2-2\bar{E}\beta(1+\phi))^2}.$$

When $0<\gamma^2<2\bar{E}\beta(1-\phi)$, $\pi_{IS}^{SC*}-\pi_{PS}^{SC*}<0$, we have $\pi_{C}^{SC*}>\ \pi_{VN}^{SC*}>\pi_{PS}^{SC*}>\pi_{IS}^{SC*}$.

When $2\bar{E}\beta(1-\phi)\leq\gamma^2\leq 2\bar{E}\beta(1-\frac{1}{2}\phi)$, $\pi_{VN}^{SC.*}-\pi_{IS}^{SC*}>0$, and $\pi_{IS}^{SC*}-\pi_{PS}^{SC*}>0$, we then obtain $\pi_{C}^{SC*}>\ \pi_{VN}^{SC*}>\pi_{IS}^{SC*}>\pi_{PS}^{SC*}$.

When $2\bar{E}\beta\left(1-\frac{1}{2}\phi\right)\leq\gamma^2\leq 2\bar{E}\beta$, $\pi_{VN}^{SC.*}-\pi_{IS}^{SC*}<0$, we then have $\pi_{C}^{SC*}>\ \pi_{IS}^{SC*}>\pi_{VN}^{SC*}>\pi_{PS}^{SC*}$.

V. NUMERICAL EXAMPLE

In this section, numerical examples are given to further elucidate the proposed four game models. The parameter values are $B=900$, $c=10$, $\bar{E}=300$, $\beta=6$, $\phi\in[0,1]$, and $\gamma\in[30,55]$. We describe the impact of the coefficient of consumer low-carbon preference γ and the coefficient of revenue retention ϕ on the optimal solutions as follows.

Based on the presentation in the figures, the main analysis results are as follows.

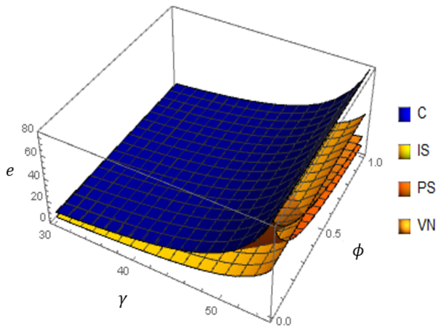

Fig. 1. The carbon-emission reduction level with γ and ϕ

1) As shown in Figure 1, the optimal carbon reduction level e is the highest in the C game, and is directly proportional to γ in the four games, is inversely proportional to ϕ in IS and VN game, and has nothing to do with ϕ in C and IS game. Figure 1 also well verifies the conclusion of Corollary 1.

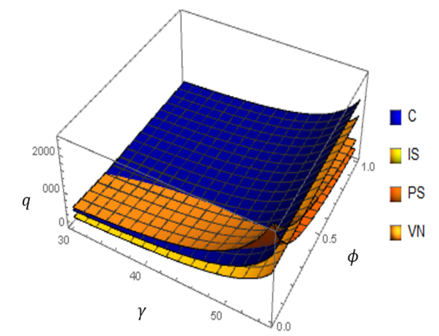

Fig. 2. The market demand with γ and ϕ

2) Based on Figure 2, the optimal market demand is directly proportional to γ in the four games, inversely proportional to ϕ in IS and VN game, and has nothing to do with

ϕ in C and IS game. As γ increases, the optimal market demand is highest in the C game and lowest in PS game. Figure 2 strongly demonstrates the conclusion of Corollary 2.

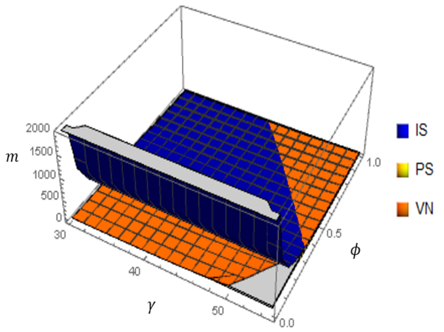

Fig. 3. The profit margin with γ and ϕ

3) Figure 3 shows that the optimal profit margin is directly proportional to γ in VN and PS game, and has nothing to do with γ in PS game, and is inversely proportional to ϕ in IS, PS and VN game. As ϕ increases, the optimal profit margin is highest in the C game and lowest in PS game. Figure 3 is closely related to the conclusion of Corollary 3.

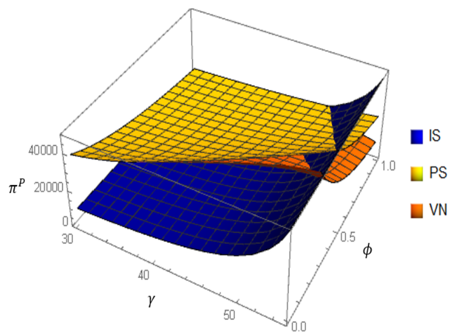

Fig. 4. The LSP's profit with γ and ϕ

4) Figure 4 displays the optimal profit of the LSP is directly proportional to γ in IS and PS game, is inversely proportional to ϕ in PS and VN game, and has nothing to do with ϕ in IS game. With a lower γ, the optimal profit of the LSP is largest in the game PS and lowest in IS. Figure 4 also well verifies the conclusion of Corollary 4.

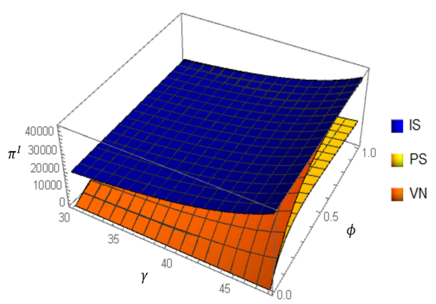

Fig. 5. The LSI's profit with γ and ϕ

5) Figure 5 demonstrates the optimal profit of the LSI is largest in the game C and smallest in PS, is directly proportional to γ in IS, PS and VN games, and is also proportional to ϕ in PS and VN game, but it has nothing to do with ϕ in IS game. Figure 5 strongly demonstrates the conclusion of Corollary 5.

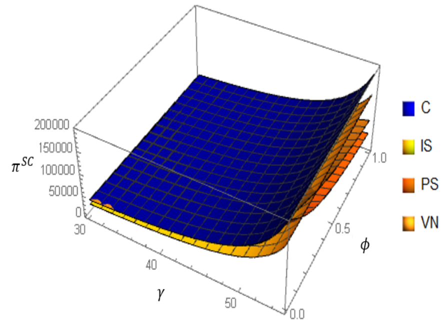

Fig. 6. The LSSC's profit with γ and ϕ

6) Based on Figure 6, the optimal overall LSSC profit is directly proportional to γ in the four games, but it is inversely proportional to ϕ in game PS and VN, and has nothing to do with ϕ in game C and IS. The optimal profit of the LSSC is largest in the game C, then lowest in game PS or IS. Figure 6 is closely related to the conclusion of Corollary 6.

VI. CONCLUSIONS

In this study, we investigated decision-making concerning LSSC joint carbon-emission reduction with a consideration of consumers' low-carbon preferences. We built four game models to study the influence of the preferences for consumers' low-carbon and revenue retention on equilibrium solutions under different power structures. Based on the results above, drawing the main conclusions are as follows.

First, power structure significantly influences the carbon reduction level, outsourcing price, and the profit of LSSC system. The optimal carbon-emission reduction level and overall profits are all the largest in the game C when making decisions as a whole, followed by the VN. The optimal outsourcing price and LSP's profit are all highest in game PS when LSP has the full control of the LSSC, followed by the game VN and IS. Furthermore, the optimal profit of the LSI is the largest in game IS when LSI dominate the LSSC, followed by game VN and PS.

Moreover, the service price and profit margin are influenced by all the power structure, consumers' low-carbon preferences and revenue retention. When $\gamma \in [30, 50]$, the profit margin is largest in game IS, followed by the VN and PS. When $\gamma \in (50, 55]$, the profit margin is largest in VN, followed by IS and PS. The trends in logistics service prices are more complex. When $\gamma \in [30, 42]$ and $\phi \in [0, 0.5]$, the logistics service price is largest in IS, followed by PS, VN, and C. When $\gamma \in [30, 42]$ and $\phi \in [0.5, 1]$, the logistics service price is largest in PS, followed by IS, VN, and C. When $\gamma \in (42, 55]$ and $\phi \in [0, 1]$, the logistics service price is highest in C, followed by IS, VN and PS.

Third, effective cooperation and appropriate competition can increase the carbon-emission reduction level, expand the logistics service market demand, and maximize the LSSC system profit. However, if the preference of consumers' low-carbon is too high, there will be a large burden on the LSP to invest in carbon-emission reduction innovation.

Fourth, in case of a Stackelberg game, a dominant power scenario of LSSC participants generates more profit.

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