

*Original Research*

# Logistics Service Supply Chain Decision-Making Analysis Considering Impact of Environment and Service Level

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## Abstract

A two-stage logistics service supply chain (LSSC) composed of one logistics service integrator (LSI) and one functional logistics service provider (LSP) is considered in this paper. It is assumed that the logistics service demand function is influenced by the LSI's service level and LSP's greening level, which can measure the impact of service quality and the environment. Under the centralized decision, LSI Stackelberg Game, LSP Stackelberg Game and Vertical-Nash decision power structure, four kinds of LSSC game models are proposed. In addition, their optimal solutions are derived and compared. Then the impact of power structures on the optimal solutions and profits are analysed. It is found that the optimal solutions are significantly influenced by the power structure, except for the optimal retail price. The greening level, service level, market demand, and overall profit of the supply chain are all the highest under centralized decision-making, followed by Vertical-Nash decision-making. Furthermore, cooperation and competition can improve the level of environmental protection and logistics industry service, and also can effectively expand the market demand and maximize the overall profit of the LSSC. Under a Stackelberg game decision-making scenario, the power of decision-rights exerts a positive impact on the profits of the LSSC participants.

**Keywords:** logistics service supply chain, different power structures, greening level, service level, game theory

## Introduction

In 2021, China's express delivery volume reached 1,083 billion pieces, contributing more than 60% to the world's express delivery growth. The express delivery industry has become a new economic growth point.

However, in different supply chain sectors, logistics and transportation are recognized as one of the significant environmental threats due to air pollution and global warming [1]. According to the ITF (International Transport Forum), 20% of global energy consumption has been related to transportation in recent years. This number is predicted to increase in the following years due to the increasing need for the transportation of products [2]. For this reason, logistics companies

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are thus facing pressure and challenges to reduce environmental impact and improve service. Hence, green and sustainability programs have become an inevitable choice for developing the global supply chain [3-5].

Many enterprises, such as Huawei, Haier, Shanghai Zhenhua Heavy, Joyoung, and Tianneng Battery in China, have been practicing green supply chain management, and they have already achieved good results [6]. To adapt to the increasingly competitive environment, logistics service supply has attained supply chain characteristics. The logistics service supply chain (LSSC) is a special type of supply chain within the service supply chain, composed of logistics service integrator (LSI) and functional logistics service provider (LSP), in which LSIs serve as the core players in general to integrate social logistics resources [7]. All production, distribution, and other associated enterprises in the LSSC to cooperate provide customers with the higher-level logistics service and minimize the adverse impact on the environment. For example, the Cainiao Network and their partners including ZTO and SF Express in China, deepened their collaboration in the green logistics industry, which will be better for improving service level and greening level, and developing positive relationships with consumers.

From a practical view, the operational performance among participants in LSSC is significantly influenced by the environment level and different power structures. Taking the Chinese Cainiao Network as an example, all the participants in the logistics platform comprise an LSSC. The Cainiao Network which dominates the LSSC has strong decision-making power in the game among others, such as ZTO, STO, and Yunda express logistics companies. Conversely, Cainiao and SF Express, have equal decision-making power and always simultaneously make decisions. Consequently, the Cainiao Network will make various decisions though its own power structures in different games. Therefore, it is necessary to explore the influence of power structures factor on decision-making in an LSSC.

The primary aim in this study is to characterize the optimal decision-making of LSSC under four power structures, with consideration of the impact of the environment and service level. The main novelty of this article is to explore the impact of environmental sustainability and service level on the LSSC from the perspective of the supply chain and four power structures. Indeed, the environmental impact and service level were rarely considered in previous studies related to LSSC decision-making.

The LSSC conforms to the trends and requirements of economic and social development and has attracted many studies. Tian (2003) first proposed that the LSSC is composed of functional LSPs, LSIs and manufacturing or retail enterprises [8]. LSSC researchers still generally follow this structure. Logistics companies have come under increasing pressure to cope with the environment and climate change in recent years. The green

transformation has become one of the most challenging problems to solve [9]. New technologies such as block chain technology and intelligent interoperable logistics are used to explore green and sustainable LSSCs [10, 11]. Consequently, making logistics more sustainable has been considered increasingly more frequently in LSSC research [12]. Packaging is also one of the most significant circular economy strategies for logistics recycling initiatives [13]. Reverse logistics has been used to support flexible and sustainable supply chain management [14].

As one of the greatest generators of emissions, the significant role of LSPs in reducing negative environmental impacts has received increasing attention. In recent study, integrated data envelopment analysis (DEA) model, an analytical framework, an empirical analysis, an improved genetic algorithm, and an investigative method were used to evaluate efficiency, competitiveness, environmental sustainability, supplier selection strategy, and the role of trust and low-carbon drivers and outcomes of LSP [2, 15-18]. In general, LSIs play decisive roles in supply chain operation. Some integrator's behavior factors can affect the sustainability of LSSC performance [19]. Under fuzzy decision environments, Wang and Hu (2021) comprehensively explored the impact of the different risk preferences on the equilibrium behavior of a green LSSC [6]. The stricter government regulations are also an additional factor that has expedited the adoption of a sustainable supply chain. Traditionally, purchasing logistics services played an important role in cost reduction and customer service improvements [12, 20].

At present, experts and scholars mainly use game theory to study the decision-making of LSSCs from the perspective of service ability cooperation and coordination, strategy selection, service quality control and behavioral preferences. Karakayali and Emir-Farinas (2007) discussed a pricing strategy for the reverse supply chain under manufacturer-dominant, recycler-dominant and centralized decision-making power structures [21]. Based on the cumulative prospect theory, Liu and Liu (2013) studied the order allocation model of a two-stage LSSC [22]. Considering demand disruption, Liu and Liu (2016) discussed a competitive LSSC coordination and proposed three coordination models to investigate the influences of demand disruption on LSSC [23]. Liu and Wang (2017) examined three power allocations in service supply chains and analyzed the impact of service level on optimal solutions [24]. With consideration of the environment, Wang and Hu (2021) proposed seven game-based models to investigate how the participants' risk preference affects the equilibrium results of the LSSC [6]. In the context of the One Belt and One Road initiative, Liu and Zhang (2018) explored supply chain coordination issues with a game-theoretical approach [25]. The influence of Fairness Concern, loss-aversion preference, risk attitude, and corporate social responsibility on quality defect guarantee decisions,

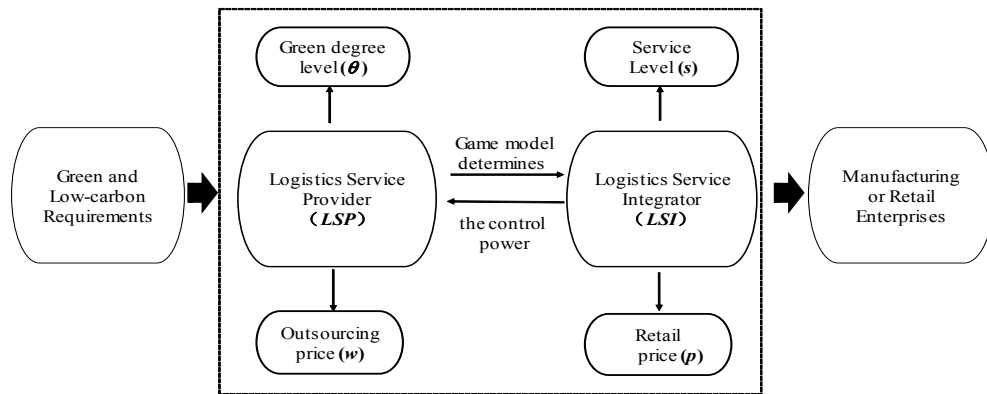


Fig. 1. The framework of the Logistics Service Supply Chain (LSSC).

service capacity procurement, quality control and coordination in the LSSC were also investigated by game theory [6, 26-29].

The exiting research of game theory provides a good reference for establishing games between the LSI and LSP in this paper. From the above discussion, there is a lack of studies on environmental sustainability and service level in the LSSC from the supply chain perspective. Some studies focused on theory about the connotations of green development, and the evaluation models, and driving factors for LSSC [1, 9, 13, 14]. In order to explore the effects of green activities, logistics services were considered as a part of the production supply chain, rather than the whole LSSC. And most previous studies have examined the role of different game power structures in LSSC but did not involve green management. Some other studies previously considered two or three games, but lacked comprehensive research on the four kinds of decision structures simultaneously.

Consequently, this paper intends to fill this gap. Considering the environmental impact and service level,

this paper discusses the decision-making problems of the LSSC under four power structures. It enriches the theoretical connotation of the LSSC and provides beneficial references for researchers and practitioners of green logistics management.

### Methods and Models

#### Methods and Problem Description

We consider a two-stage LSSC with one LSI and one LSP in the game. The LSP with an awareness of green issues provides logistics services to the LSI with an outsourcing price. Then the LSI sends logistics services to the customers by integrating the LSP's service quality. The greening level and service level are used to measure the impact of the environment and service quality from the LSP and LSI. The structure of the LSSC is shown in Fig. 1.

When supply chain participants own different power structures, they have different abilities to control the

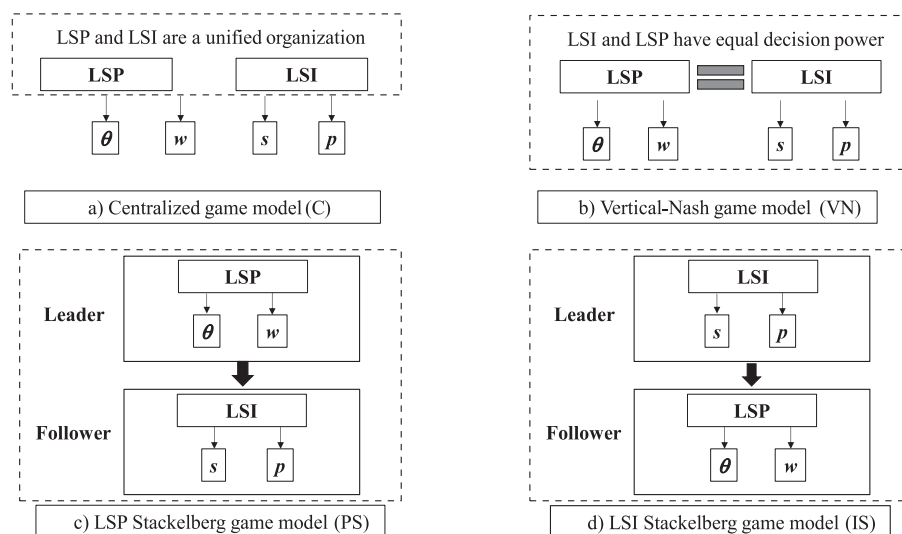


Fig. 2. Four game models of the LSSC.

Table 1. The explanation of notations.

| Notations | Meaning                                                             |
|-----------|---------------------------------------------------------------------|
| $p$       | A retail price                                                      |
| $s$       | Service level                                                       |
| $w$       | The outsource price that the LSP sells to the LSI                   |
| $c$       | The cost for the facilities and processes                           |
| $\theta$  | Greening level                                                      |
| $B$       | The total market scale                                              |
| $\beta$   | The price elasticity of the logistics service                       |
| $\gamma$  | The greening level sensitivity coefficient of the logistics service |
| $\eta$    | The service level sensitivity coefficient of the logistics service  |
| $C_p$     | The LSP's investment in technological innovation                    |
| $\xi$     | The greening innovation coefficient of logistics services           |
| $C_l$     | The LSI's investment in integrating logistics service               |
| $\sigma$  | The service innovation coefficient of the logistics service,        |
| $m$       | The LSI can obtain the marginal profit per unit of service.         |

supply chain, then they will make various decisions. Eventually, the participants will obtain various benefits. Considering various power structures, we developed four game models in Fig. 2, as depicted in (a), (b), (c), (d). We use superscript to represent the equilibrium value under the game model  $i$  ( $i = C, IS, PS, VN$ , where  $C$  denotes Centralized game,  $IS$  donates LSI game,  $PS$  donates LSP game,  $VN$  donates Vertical-Nash game), and subscript  $j$  to represent the LSSC or the participants ( $j = I, P, SC$ , where  $I$  denotes LSI,  $P$  denotes LSP, and  $SC$  denotes LSSC).

Table 1 shows the explanation of notations in models. To build the game model for LSSC decision-making, the following basic assumptions are considered in this paper.

Assumption 1. Following [10] and [24], the logistics service demand  $q$  is comprehensively affected by the market scale, retail price, green development and service level:

$$q = B - \beta p + \gamma \theta + \eta s \tag{1}$$

Assumption 2. For environmental sustainability, more technological innovations should be involved in logistics service. Hence, the LSP should bear the investment cost. We assume that the LSP's investment in technological innovation is  $C_p = \frac{1}{2} \xi \theta^2$ . This quadratic service cost function has been widely used in [1, 24, 30, 31, 32].

Assumption 3. To achieve the customer requirements, the LSI needs to integrate and improve the services provided by the LSP. The cost is also assumed to take a quadratic form,  $C_l = \frac{1}{2} \sigma s^2$ , similar

to [1] and [24]. In addition, using  $p = \bar{m} + w$ , where the LSI can obtain the marginal profit  $m$  per unit of service.

Assumption 4. To ensure the existence of the optimal solutions, we assume  $B > \beta c$ ,  $\frac{\eta^2}{\beta \sigma} < 1$ , and  $\frac{\gamma^2}{\beta \xi} < 1$ . Based on the problem description and the presented assumptions, the profit functions for the LSP, LSI and LSSC are obtained by Eq. (2) to Eq. (4):

$$\pi_p = (w - c)(B - \beta p + \gamma \theta + \eta s) - \frac{1}{2} \xi \theta^2 \tag{2}$$

$$\pi_l = (p - w)(B - \beta p + \gamma \theta + \eta s) - \frac{1}{2} \sigma s^2 \tag{3}$$

$$\pi_{sc} = (p - c)(B - \beta p + \gamma \theta + \eta s) - \frac{1}{2} \xi \theta^2 - \frac{1}{2} \sigma s^2 \tag{4}$$

### The Game Models

In this section, we develop four game models to examine the impacts of different power structures on equilibrium decisions.

#### Centralized Decisions Model(C)

Under the centralized decision-making model, the LSI and LSP form a unified organization and decide the retail price  $p$ , the greening level  $\theta$ , and service level  $s$  together to maximize the profits of the whole LSSC. The model needs to be solved under centralized decisions is:

$$Max_{\theta,p,s} [\pi_{sc}(\theta, p, s)] = (p - c)(B - \beta p + \gamma \theta + \eta s) - \frac{1}{2} \xi \theta^2 - \frac{1}{2} \sigma s^2 \tag{5}$$

Proposition 1. Under centralized decisions, if  $\frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} < 2$ , the optimal solutions of the LSI and LSP are:

$$p^{C*} = \frac{(B-\beta c)\xi\sigma}{2\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2} + c, \theta^{C*} = \frac{(B-\beta c)\gamma\sigma}{2\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2},$$

$$s^{C*} = \frac{\eta\xi(B-\beta c)}{2\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2}, q^{C*} = \frac{\beta\xi\sigma(B-\beta c)}{2\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2}.$$

Then, the optimal profit of the overall LSSC is

$$\pi_{SC}^{C*} = \frac{\xi\sigma(B-\beta c)^2}{2(2\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2)}.$$

Proof. From Eq (4), the first-order derivatives of  $\pi_{SC}$  with respect to  $p, \theta$  and  $s$  can be obtained as

$$\frac{\partial\pi_{SC}}{\partial p} = B - 2\beta p + \gamma\theta + \eta s + \beta c \tag{6}$$

$$\frac{\partial\pi_{SC}}{\partial\theta} = (p - c)\gamma - \xi\theta \tag{7}$$

$$\frac{\partial\pi_{SC}}{\partial s} = (p - c)\eta - \sigma s \tag{8}$$

The third-order Hesse matrix of  $\pi_{SC}$  is

$$H = \begin{bmatrix} \frac{\partial^2\pi_{SC}}{\partial p^2} & \frac{\partial^2\pi_{SC}}{\partial p\partial\theta} & \frac{\partial^2\pi_{SC}}{\partial p\partial s} \\ \frac{\partial^2\pi_{SC}}{\partial\theta\partial p} & \frac{\partial^2\pi_{SC}}{\partial\theta^2} & \frac{\partial^2\pi_{SC}}{\partial\theta\partial s} \\ \frac{\partial^2\pi_{SC}}{\partial s\partial p} & \frac{\partial^2\pi_{SC}}{\partial s\partial\theta} & \frac{\partial^2\pi_{SC}}{\partial s^2} \end{bmatrix} = \begin{bmatrix} -2\beta & \gamma & \eta \\ \gamma & -\xi & 0 \\ \eta & 0 & -\sigma \end{bmatrix}$$

Indeed, the Hesse Matrix of  $\pi_{SC}$  is a negative definite since  $H = \begin{bmatrix} -2\beta & \gamma & \eta \\ \gamma & -\xi & 0 \\ \eta & 0 & -\sigma \end{bmatrix} > 0$ , so  $\frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} < 2$ .

Consequently,  $\pi_{SC}$  is jointly concave in  $p, \theta$  and  $s$ . Therefore, we can obtain the unique optimal solution of

LSI and LSP by solving  $\frac{\partial\pi_{SC}}{\partial p} = 0, \frac{\partial\pi_{SC}}{\partial\theta} = 0$ , and  $\frac{\partial\pi_{SC}}{\partial s} = 0$ , which can provide  $p^{C*}, \theta^{C*}$  and  $s^{C*}$  in Proposition 1.

Combining  $p^{C*}, \theta^{C*}$  and  $s^{C*}$  into Eq. (1) and Eq. (3) will then yield the optimal demand  $p^{C*}$  and overall profit  $\pi_{SC}^{C*}$  of the LSSC under centralized decisions.

The proof of Proposition 1 is thus completed.

### Logistics Service Integrator Stackelberg Game Model (IS)

In this model, LSI and LSP represent a typical Stackelberg game, in which the LSI dominates the LSSC as the leader, while the LSP is the follower. Both the LSI and LSP maximize their profits in this scenario, and the backward induction method has to be used to solve the game model and obtain the optimal solution.

Since  $p - m + w$ , the profit function of the LSP and LSI can also be expressed as:

$$\pi_p = (w - c)[B - \beta(m + w) + \gamma\theta + \eta s] - \frac{1}{2}\xi\theta^2 \tag{9}$$

$$\pi_l = m[B - \beta(m + w) + \gamma\theta + \eta s] - \frac{1}{2}\sigma s^2 \tag{10}$$

Hence, we can obtain the logistics service integrator Stackelberg game model as:

$$\begin{aligned} \max_{m,s} \pi_l(m,s) &= m[B - \beta(m + w) + \gamma\theta + \eta s] - \frac{1}{2}\sigma s^2 \\ w, \theta &= \operatorname{argmax}(\pi_p) \\ \text{s.t.} \left\{ \begin{aligned} \max \pi_p(w, \theta) &= (w - c)[B - \beta(m + w) + \gamma\theta + \eta s] - \frac{1}{2}\xi\theta^2 \end{aligned} \right. \end{aligned} \tag{11}$$

Proposition 2. Under the LSI Stackelberg game model, if  $\frac{\eta^2}{\beta\sigma} + \frac{2\gamma^2}{\beta\xi} < 4$ , then the optimal solutions of the LSI and LSP are:

$$p^{IS*} = \frac{\sigma(B-\beta c)(3\beta\xi - \gamma^2)}{\beta(4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2)} + c, s^{IS*} = \frac{\xi\eta(B-\beta c)}{4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2},$$

$$m^{IS*} = \frac{\sigma(B-\beta c)(2\beta\xi - \gamma^2)}{\beta(4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2)}, w^{IS*} = \frac{\xi\sigma(B-\beta c)}{4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2} + c,$$

$$\theta^{IS*} = \frac{\gamma\sigma(B-\beta c)}{4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2}, q^{IS*} = \frac{\beta\xi\sigma(B-\beta c)}{4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2}.$$

Then, the optimal profit of the LSI, LSP, and overall LSSC are:

$$\pi_l^{IS*} = \frac{\sigma\xi(B-\beta c)^2}{2(4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2)}, \pi_p^{IS*} = \frac{\sigma^2\xi(2\beta\xi - \gamma^2)(B-\beta c)^2}{2(4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2)^2},$$

$$\pi_{SC}^{IS*} = \frac{\sigma\xi(6\beta\xi\sigma - 3\sigma\gamma^2 - \xi\eta^2)(B-\beta c)^2}{2 \cdot 4 \cdot -2\sigma \cdot -2 \cdot 2}.$$

Proof. We can obtain the optimal solution using the backward induction method. From Eq. (9), the first-order derivatives of  $\pi_p$  with respect to  $(w, \theta)$  can be obtained the Hesse matrix of  $\pi_p$  is  $H = \begin{bmatrix} -2\beta & \gamma \\ \gamma & -\xi \end{bmatrix}$ . Since  $\frac{\gamma^2}{\beta\xi} < 2$ , so the Hesse Matrix of  $\pi_p$  is a negative definite. Consequently,  $\pi_p$  is jointly concave in  $(w, \theta)$ . Therefore, we can obtain the unique optimal reaction function solution of the LSP is as followed.

$$w^{IS*}(m,s) = \frac{\xi}{2\beta\xi - \gamma^2}(B - \beta m + \eta s - \beta c) + c \tag{12}$$

$$\theta^{IS*}(m,s) = \frac{\gamma}{2\beta\xi - \gamma^2}(B - \beta m + \eta s - \beta c) \tag{13}$$

Combining  $w^{IS*}(m, s)$  and  $\theta^{IS*}(m, s)$  into Eq. (10), we obtain Eq. (14),

$$\pi_l^{IS} = \frac{m\beta\xi}{2\beta\xi - \gamma^2}(B - \beta m + \eta s - \beta c) - \frac{1}{2}\sigma s^2 \tag{14}$$

The first-order derivatives of  $\pi_l^{IS}$  with respect to  $m$  and  $s$  are:

$$\frac{\partial\pi_l^{IS}}{\partial m} = \frac{\beta\xi}{2\beta\xi - \gamma^2}(B - \beta m + \eta s - \beta c) - \frac{m\xi\beta^2}{2\beta\xi - \gamma^2} \tag{15}$$

$$\frac{\partial\pi_l^{IS}}{\partial s} = \frac{m\beta\xi\eta}{2\beta\xi - \gamma^2} - \sigma s \tag{16}$$

Therefore, the Hesse matrix of  $\pi_I^{IS}$  is 
$$H = \begin{vmatrix} -\frac{2\beta^2\xi}{2\beta\xi-\gamma^2} & \frac{\beta\eta\xi}{2\beta\xi-\gamma^2} \\ \frac{\beta\eta\xi}{2\beta\xi-\gamma^2} & -\sigma \end{vmatrix} > 0$$
, so the Hesse Matrix of  $\pi_I^{IS}$  is a negative definite. Consequently,  $\pi_I$  is jointly concave in  $m$  and  $s$ . Therefore, we can obtain  $m^{IS*}$  and  $s^{IS*}$ . Substituting  $m^{IS*}$  and  $s^{IS*}$  into  $w^*(m, s)$  and  $\theta^*(m, s)$  will provide  $w^{IS*}$  and  $\theta^{IS*}$ . Then, we substitute the optimal solution above into Eq. (1-4), and consider  $p = m + w$ , will yield  $q^{IS*}$ ,  $p^{IS*}$ ,  $\pi_I^{IS*}$ ,  $\pi_P^{IS*}$  and  $\pi_{SC}^{IS*}$ , which are given in Proposition 2.

The proof of Proposition 2 is thus completed.

*The Logistics Service Provider Stackelberg Game Model (PS)*

In this section, it is assumed that the LSP owns greater decision-rights on the market. Thus, the LSI and LSP represent a typical Stackelberg game, in which the LSP is the leader in LSSC, while the LSI is the follower. We can obtain the LSP Stackelberg game model as follow:

$$\begin{aligned} \max_{w,\theta} \pi_P(w, \theta) &= (w - c)[B - \beta(m + w) + \gamma\theta + \eta s] - \frac{1}{2}\xi\theta^2 \\ \text{s.t.} \quad &\begin{cases} m, s = \operatorname{argmax}(\pi_I) \\ \max \pi_I(m, s) = m[B - \beta(m + w) + \gamma\theta + \eta s] - \frac{1}{2}\sigma s^2 \end{cases} \end{aligned} \tag{17}$$

Proposition 3. Under the model dominated by the LSP, if  $\frac{2\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} < 4$ , the optimal solutions of the LSI and LSP are:

$$\begin{aligned} \theta^{PS*} &= \frac{\sigma\gamma(B-\beta c)}{4\beta\xi\sigma-2\xi\eta^2-\sigma\gamma^2}, W^{PS*} = \frac{\xi(B-\beta c)(2\beta\sigma-\eta^2)}{\beta(4\beta\xi\sigma-2\xi\eta^2-\sigma\gamma^2)} + c, \\ m^{PS*} &= \frac{\sigma\xi(B-\beta c)}{4\beta\xi\sigma-2\xi\eta^2-\sigma\gamma^2}, S^{PS*} = \frac{\xi\eta(B-\beta c)}{4\beta\xi\sigma-2\xi\eta^2-\sigma\gamma^2}, \\ p^{PS*} &= \frac{\xi(B-\beta c)(3\beta\sigma-\eta^2)}{\beta(4\beta\xi\sigma-2\xi\eta^2-\sigma\gamma^2)} + c, q^{PS*} = \frac{\beta\xi\sigma(B-\beta c)}{4\beta\xi\sigma-\sigma\gamma^2-2\xi\eta^2}. \end{aligned}$$

Then, the optimal profit of the LSI, LSP and overall LSSC are:

$$\begin{aligned} \pi_I^{PS*} &= \frac{\sigma\xi^2(2\beta\sigma-\eta^2)(B-\beta c)^2}{2(4\beta\xi\sigma-2\xi\eta^2-\sigma\gamma^2)^2}, \pi_P^{PS*} = \frac{\xi\sigma(B-\beta c)^2}{2(4\beta\xi\sigma-2\xi\eta^2-\sigma\gamma^2)}, \\ \pi_{SC}^{PS*} &= \frac{\sigma\xi(6\beta\xi\sigma-3\xi\eta^2-\sigma\gamma^2)(B-\beta c)^2}{2(4\beta\xi\sigma-2\xi\eta^2-\sigma\gamma^2)^2}. \end{aligned}$$

Proof. This proof is similar to the proof of Proposition 2.

*Vertical-Nash Game Model (VN)*

In this scenario, it is assumed that the LSI and LSP have equal decision rights on the market. Thus, they make decision simultaneously. Hence, we can obtain the Vertical-Nash game model, in which the LSI and LSP have equal power of decision-rights:

$$\begin{cases} \max_{w,\theta} \pi_P(w, \theta) = (w - c)[B - \beta(m + w) + \gamma\theta + \eta s] - \frac{1}{2}\xi\theta^2 \\ \max_{m,s} \pi_I(m, s) = m[B - \beta(m + w) + \gamma\theta + \eta s] - \frac{1}{2}\sigma s^2 \end{cases} \tag{18}$$

Proposition 4. Under Vertical-Nash game model, if  $\frac{\eta^2}{\beta\sigma} < 2$  and  $\frac{\gamma^2}{\beta\xi} < 2$ , the optimal solution of the LSI and LSP are:

$$\begin{aligned} \theta^{VN*} &= \frac{\sigma\gamma(B-\beta c)}{3\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2}, W^{VN*} = \frac{\xi\sigma(B-\beta c)}{3\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2} + c, \\ m^{VN*} &= \frac{\xi\sigma(B-\beta c)}{3\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2}, S^{VN*} = \frac{\xi\eta(B-\beta c)}{3\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2}, \\ p^{VN*} &= \frac{2\xi\sigma(B-\beta c)}{3\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2} + c, q^{VN*} = \frac{\beta\xi\sigma(B-\beta c)}{3\beta\xi\sigma-\sigma\gamma^2-\xi\eta^2}. \end{aligned}$$

Then, the optimal profit of the LSI, LSP, and overall LSSC are

$$\begin{aligned} \pi_I^{VN*} &= \frac{\sigma\xi^2(B-\beta c)^2(2\beta\sigma-\eta^2)}{2(3\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2)^2}, \pi_P^{VN*} = \frac{\xi\sigma^2(B-\beta c)^2(2\beta\xi-\gamma^2)}{2(3\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2)^2}, \\ \pi_{SC}^{VN*} &= \frac{\xi\sigma(B-\beta c)^2(4\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2)}{2(3\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2)^2}. \end{aligned}$$

Proof. This proof is similar to the proof of Proposition 2.

**Results and Discussion**

*Equilibrium Result Analysis*

The following corollaries are proposed by comparing the optimal solutions for the four kinds of power decision-making conditions.

Corollary 1. Under different power structures, there are three relationships to the greening level  $\theta$  of logistics service: 
$$\begin{cases} \theta^{C*} > \theta^{VN*} > \theta^{PS*} > \theta^{IS*}, \frac{\eta^2}{\sigma} > \frac{\gamma^2}{\xi} \\ \theta^{C*} > \theta^{VN*} > \theta^{PS*} = \theta^{IS*}, \frac{\eta^2}{\sigma} = \frac{\gamma^2}{\xi} \\ \theta^{C*} > \theta^{VN*} > \theta^{IS*} > \theta^{PS*}, \frac{\eta^2}{\sigma} < \frac{\gamma^2}{\xi} \end{cases}$$

Proof. From Proposition 1, 3, 5 and 6, we can obtain the following:

$$\begin{aligned} \frac{\theta^{C*}}{\theta^{VN*}} &= \left(1 + \frac{\beta\xi\sigma}{2\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2}\right)^2, \frac{\theta^{VN*}}{\theta^{PS*}} = \left(1 + \frac{\beta\xi\sigma-\xi\eta^2}{3\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2}\right)^2, \\ \frac{\theta^{VN*}}{\theta^{IS*}} &= \left(1 + \frac{\beta\xi\sigma-\sigma\gamma^2}{3\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2}\right)^2, \frac{\theta^{IS*}}{\theta^{PS*}} = \left(1 + \frac{\sigma\gamma^2-\xi\eta^2}{3\beta\xi\sigma-\xi\eta^2-\sigma\gamma^2}\right)^2. \end{aligned}$$

Since all parameters are non-negative,  $\frac{\eta^2}{\beta\sigma} < 1$  and  $\frac{\gamma^2}{\beta\xi} < 1$ , we obtain  $\theta^{C*} > \theta^{VN*}$ ,  $\theta^{VN*} > \theta^{IS*}$ ,  $\theta^{VN*} > \theta^{PS*}$ .

when  $\frac{\eta^2}{\sigma} > \frac{\gamma^2}{\xi}$ ,  $\frac{\theta^{IS*}}{\theta^{PS*}} < 1$ , then, we get  $\theta^{C*} > \theta^{VN*} > \theta^{PS*} > \theta^{IS*}$ ;

when  $\frac{\eta^2}{\sigma} = \frac{\gamma^2}{\xi}$ ,  $\frac{\theta^{IS*}}{\theta^{PS*}} = 1$ ; then, we get  $\theta^{C*} > \theta^{VN*} > \theta^{PS*} = \theta^{IS*}$ ;

when  $\frac{\eta^2}{\sigma} < \frac{\gamma^2}{\xi}$ ,  $\frac{\theta^{IS*}}{\theta^{PS*}} > 1$ ; then, we get  $\theta^{C*} > \theta^{VN*} > \theta^{IS*} > \theta^{PS*}$ .

Corollary 2. Under different power structures, there are three relationships to the logistics service level  $s$ :

$$\begin{cases} s^{C*} > s^{VN*} > s^{PS*} > s^{IS*}, \frac{\eta^2}{\sigma} > \frac{\gamma^2}{\xi} \\ s^{C*} > s^{VN*} > s^{PS*} = s^{IS*}, \frac{\eta^2}{\sigma} = \frac{\gamma^2}{\xi} \\ s^{C*} > s^{VN*} > s^{IS*} > s^{PS*}, \frac{\eta^2}{\sigma} < \frac{\gamma^2}{\xi} \end{cases}$$

Proof. This proof is similar to the Corollary 1.

Corollary 3. Under different power structures, there are three relationships to the market demand of logistics service.

$$\begin{cases} q^{C^*} > q^{VN^*} > q^{PS^*} > q^{IS^*}, \frac{\eta^2}{\sigma} > \frac{\gamma^2}{\xi} \\ q^{C^*} > q^{VN^*} > q^{PS^*} = q^{IS^*}, \frac{\eta^2}{\sigma} = \frac{\gamma^2}{\xi} \\ q^{C^*} > q^{VN^*} > q^{IS^*} > q^{PS^*}, \frac{\eta^2}{\sigma} < \frac{\gamma^2}{\xi} \end{cases}$$

Proof. This proof is similar to Corollary 1 too.

Corollary 1, 2, and 3 show that the different power structures significantly affect the optimal solutions of  $\theta$ ,  $s$ ,  $q$ . They are always the highest in C game, followed by the VN. The greening level is positively correlated with the service level. And these two levels promote each other and also have an important impact on the market demand.

Corollary 4. Under different power structures, there are five relationships to the price  $p$  of logistics services:

$$\begin{cases} p^{IS^*} > p^{PS^*} > p^{VN^*} > p^{C^*}, \frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} < 1 \text{ and } \frac{\eta^2}{\sigma} > \frac{\gamma^2}{\xi} \\ p^{PS^*} > p^{IS^*} > p^{VN^*} > p^{C^*}, \frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} < 1 \text{ and } \frac{\eta^2}{\sigma} < \frac{\gamma^2}{\xi} \\ p^{PS^*} = p^{IS^*} = p^{VN^*} = p^{C^*}, \frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} = 1 \\ p^{C^*} > p^{VN^*} > p^{PS^*} > p^{IS^*}, \frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} > 1 \text{ and } \frac{\eta^2}{\sigma} > \frac{\gamma^2}{\xi} \\ p^{C^*} > p^{VN^*} > p^{IS^*} > p^{PS^*}, \frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} > 1 \text{ and } \frac{\eta^2}{\sigma} < \frac{\gamma^2}{\xi} \end{cases}$$

Proof. It can be easily verified that

$$\begin{aligned} p^{IS^*} - p^{PS^*} &= \frac{(B-\beta c)(\xi\eta^2 - \sigma\gamma^2)(\beta\xi\sigma - \xi\eta^2 - \sigma\gamma^2)}{\beta(4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2)(4\beta\xi\sigma - \sigma\gamma^2 - 2\xi\eta^2)}, \\ p^{IS^*} - p^{VN^*} &= \frac{\sigma(B-\beta c)(\gamma^2 - \beta\xi)(\xi\eta^2 + \sigma\gamma^2 - \beta\xi\sigma)}{\beta(3\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2)(4\beta\xi\sigma - \sigma\gamma^2 - 2\xi\eta^2)}, \\ p^{C^*} - p^{IS^*} &= \frac{(B-\beta c)(2\beta\xi\sigma - \sigma\gamma^2)(\xi\eta^2 + \sigma\gamma^2 - \beta\xi\sigma)}{\beta(2\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2)(4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2)}, \\ p^{PS^*} - p^{VN^*} &= \frac{\xi(B-\beta c)(\eta^2 - \beta\sigma)(\xi\eta^2 + \sigma\gamma^2 - \beta\xi\sigma)}{\beta(3\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2)(4\beta\xi\sigma - \sigma\gamma^2 - 2\xi\eta^2)}. \end{aligned}$$

When  $\frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} < 1$  and  $\frac{\eta^2}{\sigma} > \frac{\gamma^2}{\xi}$ ,  $p^{IS^*} > p^{PS^*}$ ,  $p^{C^*} < p^{VN^*}$ ,  $p^{PS^*} > p^{VN^*}$ ; then, we get  $p^{IS^*} > p^{PS^*} > p^{VN^*} > p^{C^*}$ .

When  $\frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} < 1$  and  $\frac{\eta^2}{\sigma} < \frac{\gamma^2}{\xi}$ ,  $p^{IS^*} < p^{PS^*}$ ,  $p^{C^*} < p^{VN^*}$ ,  $p^{PS^*} > p^{VN^*}$ ,  $p^{IS^*} > p^{PS^*}$ ,  $p^{C^*} < p^{IS^*}$ ; then, we get  $p^{PS^*} > p^{IS^*} > p^{VN^*} > p^{C^*}$ .

When  $\frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} = 1$ ,  $p^{IS^*} = p^{PS^*}$ ,  $p^{C^*} = p^{VN^*}$ ,  $p^{PS^*} = p^{VN^*}$ ; then, we get  $p^{IS^*} = p^{PS^*} = p^{VN^*} = p^{C^*}$ .

When  $\frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} > 1$  and  $\frac{\eta^2}{\sigma} > \frac{\gamma^2}{\xi}$ ,  $p^{IS^*} < p^{PS^*}$ ,  $p^{C^*} > p^{VN^*}$ ,  $p^{PS^*} < p^{VN^*}$ ; then, we get  $p^{IS^*} < p^{PS^*} < p^{VN^*} < p^{C^*}$ .

When  $\frac{\eta^2}{\beta\sigma} + \frac{\gamma^2}{\beta\xi} > 1$  and  $\frac{\eta^2}{\sigma} < \frac{\gamma^2}{\xi}$ ,  $p^{IS^*} > p^{PS^*}$ ,  $p^{C^*} > p^{VN^*}$ ,  $p^{IS^*} < p^{VN^*}$ ; then, we get  $p^{PS^*} < p^{IS^*} < p^{VN^*} < p^{C^*}$ .

Corollary 4 implies that complex factors influence logistics service retail prices. It is closely correlated with the greening level and service level. Different power structures combined with costs and demands also give rise to corresponding changes in the retail price.

Corollary 5. Under different power structures, there is only one relationship to the logistics service outsourcing price:  $w^{PS^*} > w^{VN^*} > w^{IS^*} < p^{VN^*}$

Proof. It is easy to verify that  $w^{VN^*} - w^{IS^*} = \frac{\xi\sigma^2(B-\beta c)(\beta\xi - \gamma^2)}{(3\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2)(4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2)} > 0$ ,  $w^{VN^*} - w^{PS^*} = \frac{\xi(B-\beta c)(\gamma^2 - \beta\sigma)(2\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2)}{\beta(3\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2)(4\beta\xi\sigma - \sigma\gamma^2 - 2\xi\eta^2)} < 0$ .

Then, we can obtain  $w^{PS^*} > w^{VN^*} > w^{IS^*}$ .

Corollary 5 implies that the outsourcing price  $w$  is always the highest in PS game, followed by VN, IS game. This is because the green innovation costs of logistics services are all undertaken by the LSP, the LSP can set higher outsourcing prices though its leading power to compensate for green innovation costs.

Corollary 6. Under different power structures, the relationship to the LSI's marginal profit is as follows:

$$m^{IS^*} > m^{VN^*} > m^{PS^*}$$

Proof. It is easy to verify that  $m^{IS^*} - m^{VN^*} = \frac{(B-\beta c)(2\beta\xi\sigma - \xi\eta^2 - \sigma\gamma^2)(\beta\xi\sigma - \sigma\gamma^2)}{\beta(3\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2)(4\beta\xi\sigma - 2\sigma\gamma^2 - \xi\eta^2)} > 0$ ;

$$m^{VN^*} - m^{PS^*} = \frac{\xi^2\sigma(B-\beta c)(\beta\sigma - \eta^2)}{\beta(3\beta\xi\sigma - \sigma\gamma^2 - \xi\eta^2)(4\beta\xi\sigma - \sigma\gamma^2 - 2\xi\eta^2)} > 0$$

Then, we can obtain  $m^{IS^*} > m^{VN^*} > m^{PS^*}$ .

Corollary 7. Under different power structures, the relationship to the LSI's optimal profit  $\pi_i^*$  is as follows:  $\pi_i^{IS^*} > \pi_i^{VN^*} > \pi_i^{PS^*}$ .

Proof. It is easy to verify that:

$$\frac{\pi_i^{VN^*}}{\pi_i^{PS^*}} = \left(1 + \frac{\beta\xi\sigma - \xi\eta^2}{3\beta\xi\sigma - \xi\eta^2 - \sigma\gamma^2}\right)^2 > 1$$

$$\pi_i^{IS^*} - \pi_i^{VN^*} = \frac{\sigma^3\xi(B-\beta c)^2(\beta\xi - \gamma^2)}{2(3\beta\xi\sigma - \xi\eta^2 - \sigma\gamma^2)^2(4\beta\xi\sigma - \xi\eta^2 - 2\sigma\gamma^2)} > 0$$

Then, we can obtain  $\pi_i^{IS^*} > \pi_i^{VN^*} > \pi_i^{PS^*}$ .

Corollary 6 and Corollary 7 shows that the marginal profit and the LSI's optimal profits are the highest in IS game, followed by VN, PS game. They are all made by the LSI, who can obtain them higher by using its dominant power. Dominant power will help the supply chain participants obtain the greatest profit.

Corollary 8. Under different power structures, the relationship to the optimal profit of LSP  $\pi_p^*$  is as follows:  $\pi_p^{PS^*} > \pi_p^{VN^*} > \pi_p^{PS^*}$

Proof. It is easy to verify that,

$$\frac{\pi_p^{VN^*}}{\pi_p^{PS^*}} = \left(1 + \frac{\beta\xi\sigma - \sigma\gamma^2}{3\beta\xi\sigma - \xi\eta^2 - \sigma\gamma^2}\right)^2 > 1$$

$$\pi_p^{PS^*} - \pi_p^{VN^*} = \frac{\xi^3\sigma(B-\beta c)^2(\beta\sigma - \eta^2)}{2(3\beta\xi\sigma - \xi\eta^2 - \sigma\gamma^2)^2(4\beta\xi\sigma - \xi\eta^2 - 2\sigma\gamma^2)} > 0$$

Since all parameters are non-negative,  $\frac{\eta^2}{\beta\sigma} < 1$  and  $\frac{\gamma^2}{\beta\xi} < 1$ ,  $\pi_i^{VN^*} > \pi_i^{IS^*}$  and  $\pi_i^{PS^*} > \pi_i^{VN^*}$ . Then, we can obtain  $\pi_p^{PS^*} > \pi_p^{VN^*} > \pi_p^{IS^*}$ .

Corollary 8 shows that the LSP's optimal profit is the highest in PS game, followed by VN, IS game. It is also verified that dominant power can help the supply chain participants obtain the greatest profit in LSSC.

Corollary 9. There are three relationships to the total profit of the LSSC:

$$\text{LSSC: } \begin{cases} \pi_{SC}^{C^*} > \pi_{SC}^{VN^*} > \pi_{SC}^{PS^*} > \pi_{SC}^{IS^*}, \frac{\eta}{\sigma} > \frac{\gamma}{\xi} \\ \pi_{SC}^{C^*} > \pi_{SC}^{VN^*} > \pi_{SC}^{PS^*} = \pi_{SC}^{IS^*}, \frac{\eta^2}{\sigma} = \frac{\gamma^2}{\xi} \\ \pi_{SC}^{C^*} > \pi_{SC}^{VN^*} > \pi_{SC}^{IS^*} > \pi_{SC}^{PS^*}, \frac{\eta^2}{\sigma} < \frac{\gamma^2}{\xi} \end{cases}$$

Proof. It is easy to verify that

$$\pi_{SC}^{C*} - \pi_{SC}^{VN*} = \frac{\xi^3 \sigma^3 \beta^2 (B - \beta c)^2}{2(3\beta \xi \sigma - \xi \eta^2 - \sigma \gamma^2)^2 (2\beta \xi \sigma - \xi \eta^2 - \sigma \gamma^2)} > 0,$$

$$\pi_{SC}^{VN*} - \pi_{SC}^{PS*} = \frac{[\xi \eta^2 + \sigma \gamma^2] \eta^2 + 7\beta \xi \sigma (\beta \sigma - \eta^2) + 3\beta \sigma^2 (\beta \xi - \gamma^2)}{2(3\beta \xi \sigma - \xi \eta^2 - \sigma \gamma^2)^2 (4\beta \xi \sigma - 2\xi \eta^2 - \sigma \gamma^2)^2} > 0,$$

$$\pi_{SC}^{VN*} - \pi_{SC}^{IS*} = \frac{\xi^3 \sigma (B - \beta c)^2 (\beta \sigma - \eta^2)}{2(3\beta \xi \sigma - \xi \eta^2 - \sigma \gamma^2)^2 (4\beta \xi \sigma - 2\xi \eta^2 - \sigma \gamma^2)^2} > 0,$$

$$\pi_{SC}^{PS*} - \pi_{SC}^{IS*} = \frac{[(\eta^4 \gamma^2 + \sigma^2 \gamma^4 + 6\beta \xi \sigma^2 (\beta \xi - \gamma^2) + \xi \sigma (10\beta \xi \sigma - 4\sigma \gamma^2)) (\beta \sigma - \eta^2)]}{2(4\beta \xi \sigma - 2\xi \eta^2 - \sigma \gamma^2)^2 (4\beta \xi \sigma - \xi \eta^2 - 2\sigma \gamma^2)^2}.$$

Since all parameters are non-negative,  $\frac{\eta^2}{\beta \sigma} < 1$  and  $\frac{\gamma^2}{\beta \xi} < 1$ , thus, we obtain  $\pi_{SC}^{C*} > \pi_{SC}^{VN*}$ ,  $\pi_{SC}^{VN*} > \pi_{SC}^{PS*}$  and  $\pi_{SC}^{VN*} > \pi_{SC}^{IS*}$ .

When  $\frac{\eta^2}{\sigma} > \frac{\gamma^2}{\xi}$ ,  $\pi_{SC}^{PS*} > \pi_{SC}^{IS*}$ ; then, we get  $\pi_{SC}^{C*} > \pi_{SC}^{VN*} > \pi_{SC}^{PS*} > \pi_{SC}^{IS*}$ .

When  $\frac{\eta^2}{\sigma} = \frac{\gamma^2}{\xi}$ ,  $\pi_{SC}^{PS*} = \pi_{SC}^{IS*}$ ; then, we get  $\pi_{SC}^{C*} > \pi_{SC}^{VN*} > \pi_{SC}^{PS*} = \pi_{SC}^{IS*}$ .

When  $\frac{\eta^2}{\sigma} < \frac{\gamma^2}{\xi}$ ,  $\pi_{SC}^{PS*} < \pi_{SC}^{IS*}$ ; then, we get  $\pi_{SC}^{C*} > \pi_{SC}^{VN*} > \pi_{SC}^{IS*} > \pi_{SC}^{PS*}$ .

Corollary 9 indicates that the total profit is always the highest in C game, followed by VN game. It means that cooperation and effective competition can improve the overall profit of the LSSC.

### Numerical Discussion

This section analyzes numerical examples to further elucidate the four game models and verify the propositions and corollaries above. We describe the impacts of the greening cost coefficient  $\zeta$  and service innovation coefficient  $\sigma$  on the optimal solutions. The parameter values assumed in the numerical analysis are listed in Table 2. We set  $\zeta \in [3.5, 7]$  and  $\sigma \in [3, 6.5]$  to ensure that our analysis falls within a feasible region. To be closer to reality, the impacts of  $\zeta$  and  $\sigma$  on the LSSC models under different power structures are compared and analyzed in three situations as followed.

Table 2. The assumed parameter values.

| Parameter | $B$ | $c$ | $\beta$ | $\gamma$ | $\eta$ | $\zeta$ | $\sigma$ |
|-----------|-----|-----|---------|----------|--------|---------|----------|
| Value     | 200 | 10  | 5       | 3        | 3      | 3.5     | 3        |

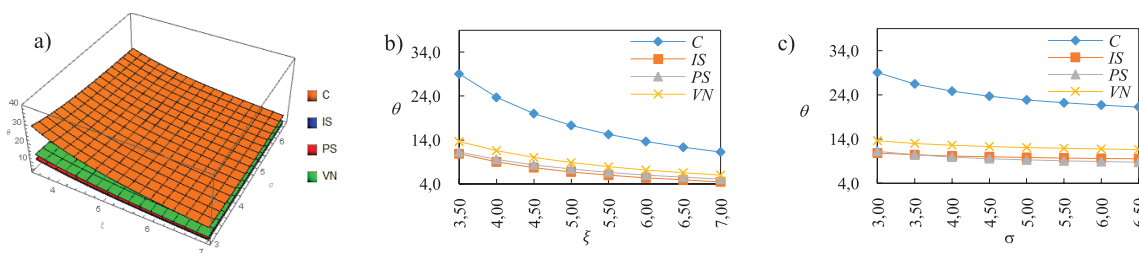


Fig. 3. Greening levels with  $\zeta$  and  $\sigma$  under different power structures. a) Greening level with  $\zeta$  and  $\sigma$ , b) Greening level with  $\zeta$ , c) Greening level with  $\sigma$ .

### Impact of $\zeta$ and $\sigma$ on $\theta$ , $s$ , $p$ and $w$

In this section, we discuss the impacts of  $\zeta$  and  $\sigma$  on the greening level  $\theta$ , service level  $s$ , retail price  $p$ , and outsourcing price  $w$ .

Fig. 3 shows the changes of greening levels with  $\zeta$  and  $\sigma$  under different power structures. From Fig. 3a), as  $\zeta$  and  $\sigma$  simultaneously increase, the greening level all decreases under the four different power structures, and the greening level is highest in C game, followed by VN, PS, and IS. From Fig. 3b) and c), when only one parameter gradually increases while the other is constant, the greening levels under the four different power structures also show a decreasing trend. However, the optimal greening level with different  $\sigma$  values is greater than that under different  $\zeta$  conditions, which are greater than the conditions under which both  $\zeta$  and  $\sigma$  simultaneously change. So, service innovation affects the greening level of logistics services. With continuous innovation, the logistics services are greener and more environmentally-friendly. In this scenario, the logistics service's greening level is constantly improved. However, when both the greening level and service level are innovated simultaneously, the greening level is lower than that of any single innovation, indicating that the more types of innovation present in the LSSC, the less innovation effects that can be achieved.

Fig. 4 shows the changes of service level with  $\zeta$  and  $\sigma$  under different power structures. From Fig. 4a), as  $\zeta$  and  $\sigma$  simultaneously increase, the service level decreases under the four different power structures. The service level is the highest in C game, followed by VN, PS, and IS game, which indicates that cooperation and effective competition among LSSC participants can improve logistics service's service levels. In Fig. 4b) and c), it can be seen that the logistics service level always decreases with  $\zeta$  or  $\sigma$  increasing under the four games. However, this is different from the phenomenon shown in Fig. 3, which indicates that the optimal service level with different  $\zeta$  values is greater than that with different  $\sigma$



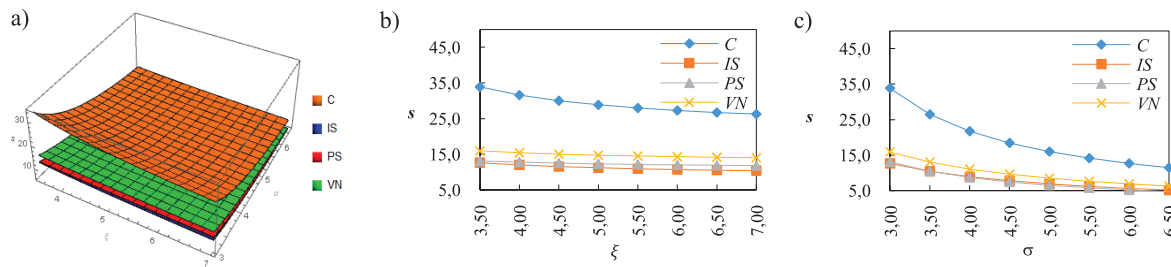


Fig. 4. Service level with  $\zeta$  and  $\sigma$  under different power structures. a) Service level with  $\zeta$  and  $\sigma$ , b) Service level with  $\zeta$ , c) Service level with  $\sigma$ .

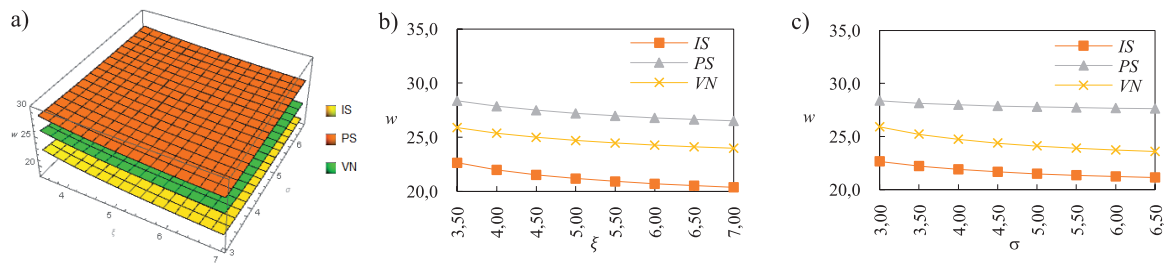


Fig. 5. Outsourcing price with  $\zeta$  and  $\sigma$  under different power structures. a) Outsourcing price with  $\zeta$  and  $\sigma$ , b) Outsourcing price with  $\zeta$ , c) Outsourcing price with  $\sigma$ .

conditions. Greening innovation also affects the service level of logistics services. With greening innovation, the logistics service’s greening level constantly improves. It verifies that the more kinds of innovation there are in the LSSC, the fewer innovation effects that can be achieved.

Fig. 5 shows the changes of outsourcing price with  $\zeta$  and  $\sigma$  under different power structures. Fig. 5a) shows that the outsourcing price decreases as  $\zeta$  and  $\sigma$  simultaneously increase under the four games. Moreover, the outsourcing price is the highest in PS game, followed by VN and IS game. From Fig. 5b) and c), by increasing  $\zeta$  or  $\sigma$  the outsourcing price always decreases. In addition, the optimal outsourcing price with a different  $\sigma$  value is greater than that under different  $\zeta$  conditions. These results indicate that since the LSP determines the outsourcing price and greening level, LSP’s ability to control service innovation is weak.

Fig. 6 shows the changes of retailer price with  $\zeta$  and  $\sigma$  under different power structures. Fig. 6a) shows that as  $\zeta$  and  $\sigma$  simultaneously increase, the retailer price decreases under the four different power structures. However, under the situation of  $\zeta = 3.5$  and  $\sigma = 3$ , the retailer price is the highest in C game, followed by VN, PS, and IS game. Under the situation of  $3.5 < \zeta \leq 7$  and  $3 < \sigma \leq 7$ , the highest retailer price is found under the IS game, followed by PS, VN and C game. From Fig. 6b) and c), it can be seen that the retailer price always decreases by increasing  $\zeta$  and  $\sigma$  under the four games. However, the optimal retailer price with different  $\zeta$  values is greater than that with different  $\sigma$  conditions. This is because the LSI determines the retailer price  $p$  and service level  $s$ , LSI’s ability to control greening innovation is weak.

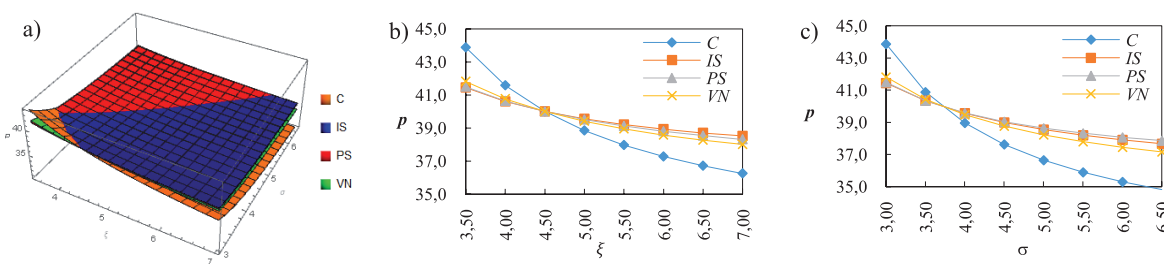


Fig. 6. Retailer price with  $\zeta$  and  $\sigma$  under different power structures. a) Retailer price with  $\zeta$  and  $\sigma$ , b) Retailer price with  $\zeta$ , c) Retailer price with  $\sigma$ .

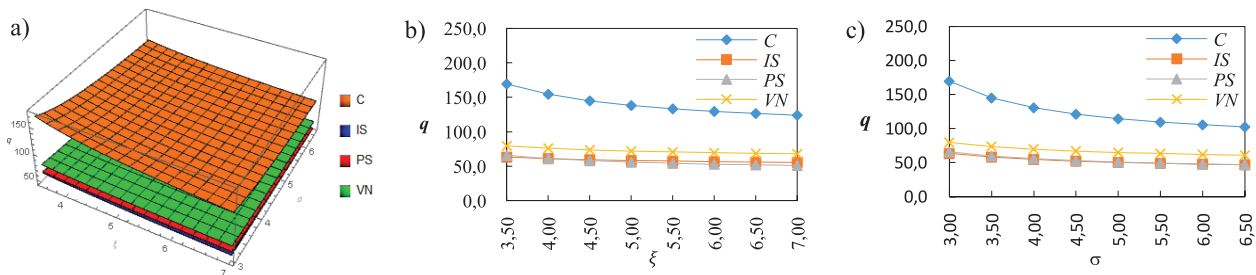


Fig. 7. Market demand with  $\zeta$  and  $\sigma$  under different power structures. a) Market demand with  $\zeta$  and  $\sigma$ , b) Market demand with  $\zeta$ , c) Market demand with  $\sigma$ .

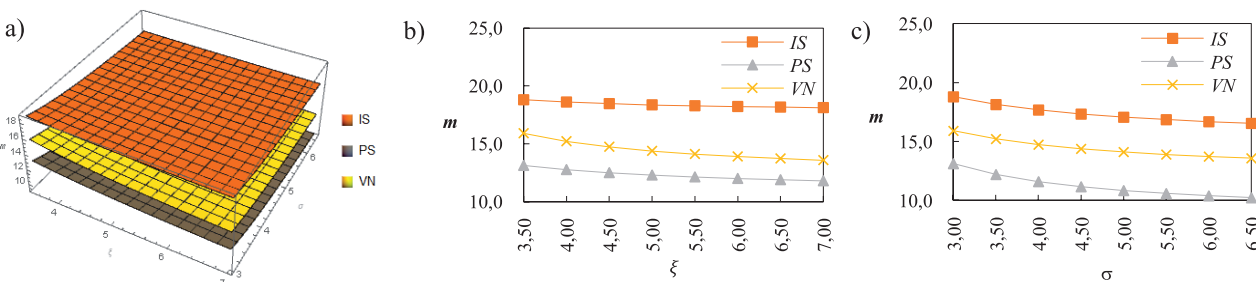


Fig. 8. Marginal profit with  $\zeta$  and  $\sigma$  under different power structures. (a) Marginal profit with  $\zeta$  and  $\sigma$ , b) Marginal profit with  $\zeta$ , c) Marginal profit with  $\sigma$ .

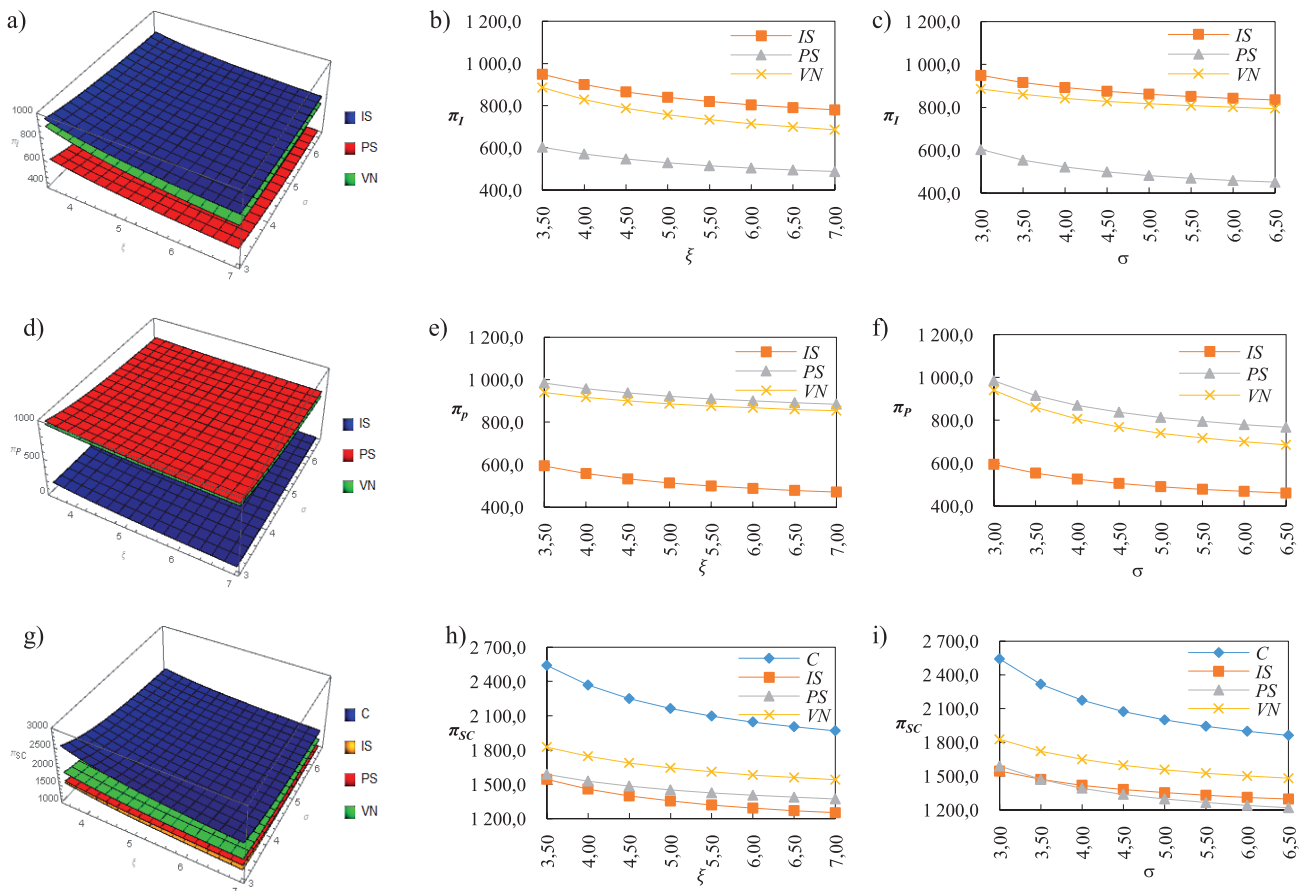


Fig. 9. Total profits with  $\zeta$  and  $\sigma$  under different power structures. a) LSI's profit with  $\zeta$  and  $\sigma$ , b) LSI's profit with  $\zeta$ , c) LSI's profit with  $\sigma$ , d) LSP's profit with  $\zeta$  and  $\sigma$ , e) LSP's profit with  $\zeta$ , f) LSP's profit with  $\sigma$ , g) Total profits with  $\zeta$  and  $\sigma$ , h) Total profits with  $\zeta$ , i) Total profits with  $\sigma$ .

### Impact of $\zeta$ and $\sigma$ on $q$ and $m$

Fig. 7 shows that market demand always decreases with  $\zeta$  and  $\sigma$  simultaneously increasing under the four different power structures. And market demand is the highest under centralized decisions, followed by VN, PS, and IS decisions, which indicates that cooperation and effective competition among LSSC participants can expand logistics services market demand. Furthermore, it can be seen that the optimal market demand with different  $\sigma$  values is greater than that under different  $\zeta$  conditions, which are greater than the conditions under which both  $\zeta$  and  $\sigma$  simultaneously change. This indicates that the market demand  $q$  is more sensitive to the logistics service innovation than the greening innovation. Improving service level can increase more market demand than improving greening level.

From Fig. 8, it can be observed that as  $\zeta$  and  $\sigma$  increase, the marginal profit decreases under the four different power structures. Further, marginal profit is the highest under IS game, followed by VN and PS game. Furthermore, it can be seen that the optimal marginal profit with different  $\zeta$  values is greater than that with different  $\sigma$  conditions. This indicates that the marginal profit is more sensitive to logistics greening than service innovation.

### Impact of $\zeta$ and $\sigma$ on $\pi_p$ , $\pi_s$ and $\pi_{sc}$

Fig. 9 shows that as  $\zeta$  and  $\sigma$  increases, the profit of LSI, LSP and the LSSC all decrease under four games. This occurs because the cost of green logistics services constantly rises with a continuous improvement of greening level and service level. Therefore, the three profits all show a downward trend. Specifically, the overall profit is the highest in C game, followed by VN, PS, and IS game. The LSI's profit is the highest under IS game, followed by VN and PS game, and the LSP's profit is the highest under PS game, followed by VN and IS game. This indicates that centralized cooperation and effective competition in LSSC can increase profit. And the leader of the LSSC can gain more profit, while the followers obtain the lowest profits. Furthermore, the optimal  $\pi_p$  with different  $\zeta$  values are greater than that with different  $\sigma$  conditions, while the optimal  $\pi_s$  with different  $\sigma$  values are greater than that with different  $\zeta$  conditions. This occurs because the LSI determines the variables of  $p$  and  $s$ . Meanwhile, the LSP decides the variables of  $w$  and  $\theta$ , so they can maximize their profits within their decision range.

## Conclusions

### The Main Conclusions

From the analysis and discussion, four main conclusions were developed as follows:

Firstly, the optimal solutions are significantly influenced by power structure, except for the optimal retail price. the greening level, service level, and market demand are always the highest in C game, followed by VN, PS, and IS game. The outsourcing price is the highest in PS game, followed by VN and IS game. The marginal profit is the highest in IS game, followed by VN and PS game. Overall, the LSP obtains the highest profits under a provider-dominated situation, followed by VN and IS game. The LSI obtains the highest profits under the integrator-dominated situation, followed by VN and PS game. The overall maximum profit of the LSSC is obtained in C game, followed by VN, PS, or IS game.

Moreover, the retail price is influenced by complex factors. It is not only affected by the power structure in the LSSC, but also closely related to the greening level and service level. Under the situation of  $3.5 \leq \zeta < 4$  and  $3 \leq \sigma < 3.5$ , the retailer price is the highest in C game, followed by VN, PS, and IS game. Under the situation of  $4 \leq \zeta < 7$  and  $3.5 \leq \sigma < 7$ , the highest retailer price is found in IS game, followed by PS, VN, C game.

Furthermore, cooperation and competition can improve the level of environmental protection and logistics service, effectively expand the market demand, and maximize the overall profit of the LSSC. However, when both the greening level and service level are innovated simultaneously, the fewer innovation effects can be achieved with limited resources.

Finally, under a Stackelberg game decision-making scenario, the power of decision-rights exerts a positive impact on the profits of the LSSC participants.

### Management Insights

Our work contributes to both researchers and practitioners. For researchers, the logistics industry is important, but it is recognized as one of the major environmental threats causing air pollution and global warming. Hence, green research on the LSSC is imperative, which can provide a better explanation of the mechanism underlying LSSC decision-making.

There are three important managerial implications of this study for practitioners. Firstly, effective cooperation among participants in the LSSC is a vital factor. Cooperation and effective competition in LSSC can reduce adverse impacts on the environment, improve service levels, and increase profits. In addition, limited innovation is necessary. With limited resources, the more kinds of innovation there are in the LSSC, the fewer innovation effects that can be achieved. Finally, dominating supply chain has a crucial role. The dominant leader of the LSSC will gain more profit. Hence, participants should strive to gain more control power.

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## Conflict of Interest

The authors declare no conflict of interest.

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