

Product pricing problem in green and non-green multi-channel supply chains under government intervention and in the presence of third-party logistics companies

Ali Mahmoudi ^a, Kannan Govindan ^{b,c,d}, Davood Shishebori ^{a,*}, Reza Mahmoudi ^e

^a Department of Industrial Engineering, Yazd University, 89195-741 Yazd, Iran

^b China Institute of FTZ Supply Chain, Shanghai Maritime University, Shanghai, 201306, China

^c Yonsei Frontier Lab, Yonsei University, Seoul, South Korea

^d Center for Sustainable Supply Chain Engineering, Department of Technology and Innovation, Danish Institute for Advanced Study, University of Southern Denmark, Campusvej 55, Odense M, Denmark

^e Department of Industrial and Systems Engineering, Isfahan University of Technology, 84156-83111 Isfahan, Iran

ARTICLE INFO

Keywords:

Sustainability
Supply chain management
Third-party logistics company
Government intervention
Game theory

ABSTRACT

Over the past decades, the significant adverse effects of economic and industrial human activities on the environment have led to the introduction of sustainability and sustainable development concepts. Based on the principles of sustainable development, in a decision/production process, managers and policymakers should not only have economic concerns but also consider social and environmental issues. In this regard, local and national governments have been convinced to intervene in supply chains mostly by imposing subsidies and/or taxes to make their activities more sustainable. Accordingly, designing sustainable supply chains has turned into a critical issue for both managers and researchers in different industries. Transportation and distribution represent two of the most unsustainable steps in any supply chain; cooperation with Third-Party Logistics (3PL) companies could help to make these steps sustainable. The main purpose of this study is to investigate the issue of sustainable supply chain management under the presence of the government and through the application of an outsourcing strategy to a 3PL company in the transportation sector. The problem is studied according to different formats of competition, decision-making, number of players, and public awareness. Considering different decision structures, the game theory is applied to model the problem and obtain the equilibrium values. Finally, a sensitivity analysis is conducted on each model, and some numerical examples are solved to show how applicable the models are. The results show that cooperation with 3PLs in a supply chain enhances the public awareness about environmental issues and promotes the sustainability of the supply chain. Governmental tariffs can also serve as practical tools to push supply chains towards sustainable strategies.

1. Introduction

During the last century, businesses mainly focused on making more profit by developing new industries, establishing new factories, and elevating the level of production. However, focusing on financial issues and trying to optimize economic objectives has proved to exert serious adverse effects on the environment and societies (Barari, Agarwal, Zhang, Mahanty, & Tiwari, 2012). For example, accelerating the production of steel products to increase profits without considering environmental issues increases the rate of pollution. This gives a rise to

pollution-induced illnesses such as respiratory diseases and certain cancers (Chen, He, Zhang, Jiang, & Wang, 2017). As another example, the forestry industry gains more profit by cutting down a vast number of trees but may also destroy a forest or decimate some plant or animal species. The transportation system is another domain where profit incentives may lead to unsustainability in both the society and the environment (Mahmoudi, Shetab-Boushehri, Hejazi, & Emrouznejad, 2019; Mahmoudi, Shetab-Boushehri, Hejazi, Emrouznejad, & Rajabi, 2019). To control these detrimental effects, the concept of 'sustainable development' was introduced in the 1980s. Soon after, the concept turned

* Corresponding author.

E-mail addresses: j.mahmoudi.ali@gmail.com (A. Mahmoudi), kgov@iti.sdu.dk (K. Govindan), Shishebori@yazd.ac.ir (D. Shishebori), j.mahmoudi.reza@gmail.com (R. Mahmoudi).

<https://doi.org/10.1016/j.cie.2021.107490>

Received 9 June 2020; Received in revised form 14 May 2021; Accepted 17 June 2021

Available online 26 June 2021

0360-8352/© 2021 Elsevier Ltd. All rights reserved.

into one of the main concerns of scholars in the new millennium (Mahmoudi & Rasti-Barzoki, 2018a).

The concept of Green Supply Chain Management (GSCM) is an important subject that has attracted the attention of researchers in the field of Supply Chain (SC) management (Hafezalkotob, 2015). Indeed, GSCM is a field motivated by sustainable development ideas. A fundamental difference between a Green Supply Chain (GSC) and a regular non-green one is simply that green activities are performed for at least one level of the SC, e.g., production level. In fact, in green supply chains, managers willingly seek to make their activities more eco-friendly (Srivastava, 2007).

Over the past few decades, the number of studies on competitive markets, product prices, delivery methods, and advertisement in SCs has significantly increased (Hafezalkotob, Mahmoudi, Hajisami, & Wee, 2018). Due to the production and distribution of products, manufacturers have a significant role in SCs. They can distribute their products to customers through different channels, e.g., through retailers, by direct delivery, or a combination of the two (dual channel). In an indirect mode, products are shipped from the producer to the retailer, and then the retailer sells the products to the customer. In a direct channel, the producer fulfills the customer's orders without any intermediaries. In dual channel SCs, producers distribute their products through both direct and indirect channels. This distribution system has been used by several companies including Apple, IBM, and Dell (Huang, Yang, & Liu, 2013).

In addition to the structure of distribution channels, the logistics process is a critical issue for SC managers. Given the growth in customer demand and technology, achieving optimal logistics imposes major costs on companies (Rodrigues, Martins, Wanke, & Siegler, 2018). Therefore, in order to raise profits and reduce costs, large companies outsource some of their activities to institutions or companies that provide logistic services. On the other hand, the transportation stage is one of the most important stages in any SC that has undesirable environmental impacts. According to Mahmoudi, Emrouznejad, Shetab-Boushehri, and Hejazi (2020), about 14% of released pollution in the world each year has been produced by the transportation industry. Because of this, recently it can be seen that in all industries doing more sustainable transportation activities has turned to be an effective strategy to achieve sustainable development goals. In particular, this shows that managing the environmental side of transportation activities can improve the sustainability of the SC by reducing released carbon emissions (Zhu, Sarkis, & Lai, 2008). Outsourcing of logistic services can have a positive impact on the reduction of logistics costs, environmental pollution, delay of goods delivery to customers, and additional service charges (Giri & Sarker, 2017). As the logistic service providers, Third-Party Logistics (3PL) companies started to be a part of SCs in the late 1980s. The activities outsourced to 3PL companies can include all or a specific part of the logistic activities of a company (Lieb, 1992). As an advantage of cooperation with the 3PLs, companies can focus on their fields of specialization by outsourcing logistics to outside providers. 3PLs upgrade their information systems and equipment as specifications evolve and technology progresses. Companies benefit from the versatility provided by 3PLs providers. Another superiority of cooperation with the 3PLs is that they save money by using big trucks and warehouses. This also helps to have more sustainable transportation activities in the SC (Jamali & Rasti-Barzoki, 2019; Kayvanfar, Husseini, Karimi, & Sajadieh, 2017).

Given the importance of green activities and sustainability in SCs, local and national governments all around the world have been convinced to intervene in the activities of SCs (Hafezalkotob, 2015). Although governments monitor all the activities in a SC, they mostly focus on the production stage and try to make it more sustainable by imposing subsidies and/or taxes (Mahmoudi & Rasti-Barzoki, 2018a).

Recent studies have shown that government financial policies can affect SC processes and their sustainability remarkably (Sheu & Chen, 2012). In this line, the present study mainly aims to investigate the impacts of governments' interventions and cooperation with the 3PL companies on the decisions of the other members in a supply chain. The issue of sustainability is also explored in SCs and public reactions. The study specifically contributes to the literature by answering the following critical questions:

1. How does cooperation with 3PL companies affect the sustainability of SCs?
2. What are the equilibrium values of wholesale and retail prices, demands, and stakeholders' profits in different channels?
3. How do government intervention scenarios affect the Equilibrium Values (EVs) and the stakeholders' behavior?
4. How can public awareness, mass media, and marketing activities affect the sustainability of SCs?
5. Which governmental strategy is the most effective, and why?

To answer these questions, the Game Theory (GT) will be applied as a basis for modelling the problem of government intervention, GSCM, and cooperation with 3PL companies in different distribution channels and market/player/game structures.

The rest of this paper is organized in several sections. Section 2 reviews a number of studies in the literature. Section 3 presents a list of the symbols used in mathematical models, main assumptions, problem definitions, and a GT model for each problem. The government model is presented in Section 4. Sensitivity analyses are conducted and numerical examples are discussed in Section 5. Finally, the conclusion and a few suggestions for future research are given in Section 6.

2. Literature review

GSCM is an important concept in the field of Sustainable Supply Chains (SSCs), and many studies have recently been conducted on it. Product pricing, pollution control, product distribution, recycling, etc. are some of the issues that have been studied in SCs. For instance, Zhang, Wang, and Ren (2014) studied a SC including a supplier and a retailer. In their model, the producer assigned the wholesale price and the energy level, but the retailer set the retail price. Their analyses indicated that, when consumers have different appraisements about a product, the product cost directly affects their preference. Rezaee, Dehghanian, Fahimnia, and Beamon (2017) designed a GSC in a carbon transact environment. They concluded that there is a positive nonlinear relationship between the budget availability and carbon price for the reconfiguration of SCs and the greening of SCs. Liu, Li, Ren, and Forrest (2020) studied the pricing problem in a dual-channel SC for two different products. In this study, GT was used to determine the best strategy. The results showed that the manufacturer can sell products that are popular with consumers in the direct channel to earn more profit and avoid selling products in indirect channels. Karimabadi, Arshadi-khamseh, and Naderi (2020) explored the same problem and analyzed it in a fuzzy environment using the GT approach. They considered the cost of producing products and the amount of demand fuzzy.

With an expansion in the outsourcing of logistics activities in various industries during recent years, authors have shown great interest in examining the role of logistics companies in the SC. For example, using GT, Jiang, Wang, and Yan (2014) formulated the issue of decision-making and coordination in a SC. In their study, the producer cooperated with the logistics company to decrease the service costs, and the retailers competed for product sales and cooperation with 3PL companies. Huang and Wang (2017) developed a Closed-Loop Supply Chain

(CLSC) including a producer, a distributor, and a 3PL company. The producer was the leader of the channel, trying to cooperate with the distributor and the 3PL company through licensing the technology. They analyzed the impacts of the ability to remanufacture the SC components on environmental sustainability. Xu, Liu, and Chen (2017) proposed a model to investigate the problem of the vehicle scheduling problem in an SCM that cooperates with a 3PL. They applied the Ant Colony Optimization algorithm to solve the proposed scheduling strategies. Using a two-stage stochastic programming model, Kayvanfar, Moattar Husseini, Karimi, and Sajadieh (2018) modeled the activities of companies considering a supply–demand hub in industrial clusters as a public logistics services provider. They assumed that a 3PL will provide the logistic services, then applied the Benders decomposition algorithm to solve the proposed models. Huang, Fan, and Wang (2019) considered an SC including a supplier, a retailer, and a 3PL; then they evaluated the effects of the transportation fees of 3PL on the SC's members' performance.

Huang et al. (2019) studied the effect of transportation costs on the performance of SC members. The examined SC included a retailer, a 3PL company and a supplier. As it was found, when a logistics company offers variable transit costs, the demand rises. Wang, Yang, Zhuo, and Xiong (2019) investigated a problem including a 3PL company offering integrated logistics and financial services to a budget-constrained producer with varying risk preferences. They applied a mean-standard deviation objective function to evaluate the impacts of different risk preferences and the demand volatilities on the equilibrium interest rate. Kayvanfar, Husseini, NengSheng, Karimi, and Sajadieh (2019) developed three mathematical models to optimize the interactions of

businesses situated within industrial clusters using a supply–demand hub in industrial clusters as a conjoint logistics and depository facilities provider for small/medium-sized companies as the producers. They assumed that all of the interactions are being supervised by a 3PL.

Due to the importance of environmental issues and the growing social concerns in this regard, governments are increasingly willing to interfere with the activities of SC members. Hence, some researchers have begun to consider the government as one of the players in their studies and have examined different strategies and problems. For example, Mahmoudi, Hafezalkotob, and Makui (2014) showed how government regulations can change power plants activities and energy supply. Their analysis indicated that, after government subsidies and/or taxes, power plants tend to use more sustainable energy sources to generate electricity. Mahmoudi and Rasti-Barzoki (2018a) applied an evolutionary game model to evaluate the short and long-term consequences of the financial policies of governments. Considering a real case, they showed that financial intervention is a very effective and practical strategy, especially in long-term processes. However, they only analyzed one-channel SCs and did not consider logistics and transportation activities. Considering three return pricing scenarios and using the concept of GT, Javadi, Alizadeh-Basban, Asian, and Hafezalkotob (2019) developed a price-energy-saving model to study the performance of a dual-channel GSC under government surveillance. In another study by Halat and Hafezalkotob (2019), government policies were analyzed in connection to carbon emissions in a SC. They formulated the interactions among the players with a Stackelberg game structure and emphasized that governmental policies can have direct positive impacts on the performance of SCs.

Table 1
Key differences between the current study and some other studies.

References	GSCM	Pricing	Pollution	3PLs	Multi-channel structure	Dual-channel structure	Public awareness	Government intervention	Different scenarios	Method
Yan and Pei (2009)	✓	✓				✓				GT
Hua, Wang, and Cheng (2010)		✓				✓				GT
Yan et al. (2011)		✓			✓					GT
Sheu and Chen (2012)	✓	✓						✓	✓	GT
Ghosh and Shah (2012)	✓	✓						✓		GT
Cao and Zhang (2013)	✓	✓								GT
Amrouche and Yan (2013)	✓	✓				✓				GT
Zhang et al. (2014)	✓	✓			✓		✓			GT
Jiang et al. (2014)		✓		✓	✓					GT
Maiti and Giri (2015)		✓		✓	✓					GT
Li, Hou, Chen, and Li (2016)	✓	✓				✓				GT
Huang, Wang, Zhang, and Pang (2016)	✓	✓	✓	✓	✓					GT
Xu et al. (2017)	✓			✓	✓					ACO
Hafezalkotob and Mahmoudi (2017)	✓	✓	✓		✓			✓	✓	EGT
Wang, Song, and Wang (2017)		✓				✓				GT
Qi, Wang, and Bai (2017)		✓	✓			✓				GT
Kayvanfar, Sajadieh, Husseini, and Karimi (2018)				✓	✓					RMCGP
Zhao, Wei, and Li (2018)		✓				✓				GT
Mahmoudi and Rasti-Barzoki (2018b)	✓	✓	✓			✓	✓	✓	✓	EGT
Kayvanfar et al. (2019)				✓	✓					LRBH
Huang et al. (2019)		✓		✓		✓				EGT
Daryanto, Wee, and Astanti (2019)			✓	✓		✓				Heuristic
Taleizadeh, Haghghi, and Niaki (2019)	✓	✓	✓		✓					MOMIP
Abbasi, Saboury, and Jabalameli (2021)				✓						MINLP
Current research	✓	✓	✓	✓	✓	✓	✓	✓	✓	GT

Note. Game Theory (GT), Evolutionary Game Theory (EGT), Multi-Objective Mixed Integer Programs (MOMIP), Ant Colony Optimization (ACO), Revised Multi-Choice Goal Programming (RMCGP), Linear Relaxation-Based Heuristic (LRBH), Mixed Integer Non-Linear Programming (MINLP).

Although there is a significant number of studies focused on GSCM, there are just a few studies in the field that have investigated logistics issues beside production stages, particularly cooperation with 3PL companies. In addition, almost all of the existing studies related to GSCM and 3PL are only conducted in a one-channel distribution structure, whereas large companies currently use multi-channel structures. Hence, considering a multi-channel structure to achieve more practical results is essential. Finally, marketing strategies and public awareness can seriously affect the sustainability of a SC (Mahmoudi & Rasti-Barzoki, 2018a). This is an important but missing point in all the studies in the field of GSCM and 3PL, but it will be addressed in the current study.

To conduct a comprehensive study, three different games are included and three different mathematical models are developed to study the games. Considering the most important features of SCs, an overview of the differences between the current study and the selected similar studies is provided in Table 1.

3. Problem statement

In order to better investigate the importance of cooperation with third-party logistics companies and the impact of public awareness on supply chain sustainability, three different issues with different structures are studied in the present research. Also, to better simulate the problem and make the management results more practical, the government is considered as one of the main actors in the supply chains in all the three problems. The problems are studied in two different scenarios. In the first one, the goal is to examine the conditions of sustainability in a situation where the government is more in pursuit of its financial interests. The second scenario, on the other hand, examines the sustainability of supply chains with the aim of minimizing the amount of pollution set by the government.

3.1. List of symbols

The indexes, parameters and variables used in this study are as follows:

Indexes	
I	set of producers, indexed by $i \in I = \{1, 2, \dots, I \}$
R	set of 3PLs, indexed by $r \in R = \{1, 2, \dots, R \}$
J	set of retailers, indexed by $j \in J = \{1, 2, \dots, J \}$
S	set of channels, indexed by $s \in S = \{1, 2, \dots, S \}$
Y	set of 3PL channels, indexed by $y \in Y \subseteq S$
L	set of pollution types, indexed by $l \in L = \{1, 2, \dots, L \}$
Parameters	
α_s	the market base in channel s
λ_i	the impact of the greenness degree of the product on the demand of producer i
β	the self-price elasticity in the demand function
γ	the cross-price elasticity of the demand
η_i	the cost coefficient of the green degree for producer i
χ_s	the transportation cost of each item by the producer in channel s
ζ	the shipping cost of each item for 3PL
f_i	the production cost of each item for producers i
k	the coefficient of the presence of 3PL in the channel
e^s	the importance of cooperation with 3PL, $e^s \geq 0$
CP_l	the emission cost of the released gas type l
RU_j	the reservation profit considered by retailer j
RUM_i	the reservation profit considered by producer i
RUT_r	the reservation profit considered by 3PL provider r
RUG	the reservation profit considered by the government
MP_G	the upper limit of the total pollution released by the SCs, as considered by the government
Decision variables	
p_j	the product price for retailer j
p_d	the product price in the direct channel for producer i
θ_i	the greenness degree of the product in producer i
w_i	wholesale price for producer i
c_i	

(continued on next column)

(continued)

Indexes	
	the cost of transporting each item from the producer to the retailer by 3PL ($c_i > \zeta$)
φ_i	the tariff assigned to producer i by the government (If φ_i is positive, the government will subsidize producer i . Negative φ_i means tax.)
Dependent variables	
Q_s	the amount of demand through channel s
π_j	the profit function of retailer j
π_{3pl}	the profit function of 3PL
π_{M_i}	the profit function of producer i

3.2. Assumptions

The main assumptions made in this study to model the competition among the agents of SCs are as follows:

Assumption 1. The retail prices are higher than the wholesale prices. Also, the wholesale prices and those in the direct channel are higher than the total production cost ($p_j > w_i > c_{total}$). This is a rational and fundamental assumption made in many studies (Li, Zhu, Jiang, & Li, 2016).

Assumption 2. To keep the demand value as a non-negative value (there is no negative demand value in the real world), it is assumed that the market base demand is large enough and noticeably higher than the other parameters (Swami & Shah, 2013).

Assumption 3. The self-price elasticity in a channel is always bigger than the cross-price elasticity in the other channels ($\beta > \gamma > 0$) (Chen, Fang, & Wen, 2013).

Assumption 4. The value of the self-price elasticity of producer i is bigger than the demand sensitivity to the greenness degree ($\beta > \lambda_i > 0$) (Li, Zhu, et al., 2016).

3.3. Problem formulation

In this section, different game structures are analyzed, and a game-theoretic approach is proposed to study each game.

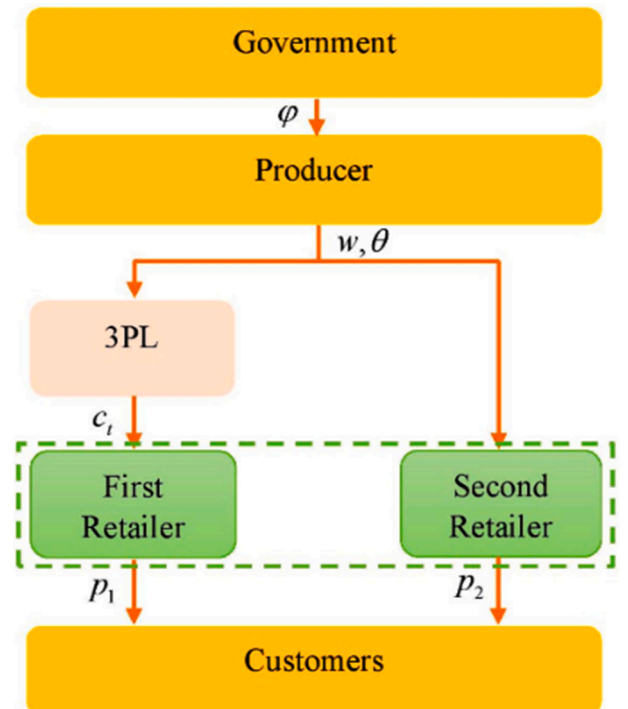


Fig. 1. The general scheme of the game in Problem I.

3.3.1. Problem I: A set of one producer, one 3PL firm, and two retailers

In this first problem, a GSC including a producer, a 3PL firm and two retailers is taken into consideration. The customers can order the products through two indirect channels and buy them from the retailers. The main difference between the channels lies in the transportation process. It is assumed that, in the first channel, the products will be transported by a 3PL company. The government monitors the activities of the producer and imposes a specific level of tariff. The schematic diagram of the first problem is given in Fig. 1.

3.3.1.1. The demand functions. The demand function for each channel is considered in a linear form, which is in accordance with many studies in the literature such as (Yan, Guo, Wang, & Amrouche, 2011; Yao, Leung, & Lai, 2008). The demand in a specific channel depends on the price of the product in that channel as well as in the other channels. Similar to some previous studies (Gao, Han, Hou, & Wang, 2016; Li, Zhu, et al., 2016), the greenness degree is considered as another factor affecting the demand function. A 3PL company is included in the first channel to make transportation process more sustainable, which will bring an advantage to this channel. The advantage of the 3PL component (A^{3pl}) is defined as follows and added to the demand function (Mahmoudi & Rasti-Barzoki, 2018a):

$$A^{3pl} = k \times e^g \quad (1)$$

Based on the explanations and the assumptions, the demand objective functions for the first and the second channels are represented in Eqs. (2) and (3):

$$Q_1 = \alpha_1 - \beta p_1 + \gamma p_2 + \lambda \theta + A^{3pl} \quad (2)$$

$$Q_2 = \alpha_2 - \beta p_2 + \gamma p_1 + \lambda \theta \quad (3)$$

where Q_1 is the demand in the first channel, p_1 and p_2 are the price of the product in the first and the second channels respectively, θ is the greenness degree of the product, and A^{3pl} is the 3PL advantage. Q_2 follows the same naming logic, simply without the 3PL that is present in Q_1 .

3.3.1.2. The profit functions for each player. It is assumed that the shipping costs in the channel with 3PL will be paid by the retailer, and the retailer buys the products at wholesale prices (w) from the producer. In the channel without 3PL, however, it is the producer that will pay all the shipping costs. Accordingly, the profit function of the first and the second retailers can be defined as follows:

$$\pi_1 = (p_1 - w - c_i)Q_1 \quad (4)$$

$$\pi_2 = (p_2 - w)Q_2 \quad (5)$$

The revenue of the 3PL company is the costs that the retailers pay for shipping the products. If ξ is taken as the shipping cost per unit for the 3PL company ($c_i > \xi$), the profit function of 3PL is:

$$\pi_{3pl} = (c_i - \xi)Q_1 \quad (6)$$

In addition, the government is supposed to have a leadership role in this game. By monitoring the producer's activities, the government will influence the decision-making process through financial intervention or tariffs (φ). Considering all the costs and incomes, the profit function of the producer is:

$$\pi_M = (w + \varphi - f)Q_1 + (w + \varphi - f - \chi)Q_2 - \eta \frac{\theta^2}{2} \quad (7)$$

To produce green products, the producer has to apply a green production system, which costs more than a regular system. According to previous studies (Ghosh & Shah, 2012; Li, Zhu, et al., 2016), the cost is equal to function $\eta \frac{\theta^2}{2}$. This is called the greening cost.

3.3.1.3. The equilibrium values in Problem I. In this section, it is assumed

that the competition among the players at the same level, i.e., producer with producer and retailer with retailer, is a Nash competition. There is also a Stackelberg game among different levels, where the player at the upper level is the leader for the players at the lower levels in the same SC. Hence, the government is the leader for the producers, and a producer is a leader for its retailer(s) and 3PL. The decision-making structure and the sequences for the first game are as follows:

$$\left\{ \begin{array}{l} \text{Max}_{\varphi} \pi_G \\ \text{Max}_{\pi_M} = (w + \varphi - c)Q_1 + (w + \varphi - c - \chi)Q_2 - \eta \frac{\theta^2}{2} \\ \text{Max}_{\pi_{3pl}} = (c_i - \xi)Q_{1c_i} \\ \left\{ \begin{array}{l} \text{Max}_{\pi_2} = (p_2 - w)Q_{2p_2} \\ \text{Max}_{\pi_1} = (p_1 - w - c_i)Q_{1p_1} \end{array} \right. \end{array} \right. \quad (8)$$

Lemma 1. To obtain the Nash Equilibrium (NE) values of p_1 and p_2 , the following equation must be solved:

$$\left\{ \begin{array}{l} \frac{d\pi_1}{dp_1} = 0 \rightarrow e^g k + w\beta + \beta c_i - 2\beta p_1 + \gamma p_2 + \alpha_1 + \theta\lambda = 0 \\ \frac{d\pi_2}{dp_2} = 0 \rightarrow w\beta + \gamma p_1 - 2\beta p_2 + \alpha_2 + \theta\lambda = 0 \end{array} \right. \quad (9)$$

$$\quad (10)$$

Proof. Solving Eqs. (9) and (10) results in the following equilibrium prices:

$$p_1^* = \frac{2e^g k\beta + (2\beta + \gamma)(w\beta + \theta\lambda) + 2\beta(\beta c_i + \alpha_1) + \gamma\alpha_2}{4\beta^2 - \gamma^2} \quad (11)$$

$$p_2^* = \frac{e^g k\gamma + (2\beta + \gamma)(w\beta + \theta\lambda) + \beta\gamma c_i + \gamma\alpha_1 + 2\beta\alpha_2}{4\beta^2 - \gamma^2} \quad (12)$$

Lemma 2. The equilibrium amount of c_i is:

$$c_i^* = \frac{2e^g k\beta - (2\beta + \gamma)(w(\beta - \gamma) - \theta\lambda) + \xi A_1 + 2\beta\alpha_1 + \gamma\alpha_2}{2A_1} \quad (13)$$

Proof. Eq. (13) is the result of the following equation:

$$\frac{d\pi_{3pl}}{dc_i} = 0 \rightarrow \frac{\beta(2e^g k\beta - (2\beta + \gamma)(w(\beta - \gamma) - \theta\lambda) + A_1(\xi - 2c_i) + 2\beta\alpha_1 + \gamma\alpha_2)}{4\beta^2 - \gamma^2} = 0 \quad (14)$$

Note. In the whole paper, A_i is the i^{th} change of the variable. Because of the great number of changes in the variables and for the purpose of keeping the paper brief, a complete account for all those changes is given in the [Supplementary file](#).

Following the Stackelberg game sequences, to calculate the EVs for the decision variables of the producer, the EVs obtained for the retailers and the 3PL must first be replaced in Eq. (7). Then, new EVs are calculated from the obtained profit function.

Lemma 3. The EVs of the wholesale price and the greenness degree are:

$$w^* = - \frac{\eta\varphi A_6 + (\varphi A_2 + A_4)A_7 + \eta A_8}{\eta A_5 + A_2 A_7} \quad (15)$$

$$\theta^* = \frac{A_4 A_5 + A_2 (\varphi A_5 - \varphi A_6 - A_8)}{\eta A_5 + A_2 A_7} \quad (16)$$

Proof. To obtain the EVs, the following set of equations must be solved:

$$\begin{cases} \frac{d\pi_M}{d\theta} = 0 \rightarrow -\eta\theta + (w + \varphi)A_2 + A_4 = 0 \\ \frac{d\pi_M}{dw} = 0 \rightarrow wA_5 + \varphi A_6 + \theta A_7 + A_8 = 0 \end{cases} \quad (17)$$

$$(18)$$

3.3.2. Problem II: A set of one producer, one 3PL firm, two retailers, and one direct channel

For the second problem, a GSC including a producer, a 3PL company, and two retailers are taken into consideration. The SC has three channels including one direct channel and two indirect channels. Moreover, the 3PL component is responsible for delivering the products from the producer and transporting them to the second retailer. In the direct channel, the producer delivers the products to consumers directly. As in the first problem, in the first retail channel and the direct channel, the producer pays the shipping cost. In the 3PL channel, however, it is the retailer that pays the shipping costs. The schematic diagram of Problem II is shown in Fig. 2.

3.3.2.1. The demand functions. Based on the above explanations, the demand functions for the three channels are as follows:

$$Q_1 = \alpha_1 - \beta p_d + \gamma(p_1 + p_2) + \lambda\theta \quad (19)$$

$$Q_2 = \alpha_2 - \beta p_1 + \gamma(p_d + p_2) + \lambda\theta \quad (20)$$

$$Q_3 = \alpha_3 - \beta p_2 + \gamma(p_d + p_1) + \lambda\theta + A^{3pl} \quad (21)$$

3.3.2.2. The profit functions for each player. The profit objective functions for the first and the second retailers are as follows:

$$\pi_1 = Q_2(p_1 - w) \quad (22)$$

$$\pi_2 = Q_3(p_2 - w - c_t) \quad (23)$$

The shipping costs paid by the second retailer form the revenue of the 3PL company are as follows:

$$\pi_{3pl} = (c_t - \xi)Q_3 \quad (24)$$

Finally, the profit of the producer can be calculated using Eq. (25):

$$\pi_M = (p_d - f + \varphi - \chi_1)Q_1 + (w - f + \varphi - \chi_2)Q_2 + (w - f + \varphi)Q_3 - \eta \frac{\theta^2}{2} \quad (25)$$

3.3.2.3. The equilibrium values in Problem II. The decision-making sequences for Problem II are presented in Eq. (26):

$$\left\{ \begin{array}{l} \text{Max}_{\varphi} \pi_G \\ \text{Max}_{w, \theta, p_d} \pi_M = (p_d - f + \varphi - \chi_1)Q_1 + (w - f + \varphi - \chi_2)Q_2 + (w - f + \varphi)Q_3 - \eta \frac{\theta^2}{2} \\ \text{Max}_{c_t} \pi_{3pl} = (c_t - \xi)Q_3 \\ \left\{ \begin{array}{l} \text{Max}_{p_2} \pi_2 = (p_2 - w - c_t)Q_3 \\ \text{Max}_{p_1} \pi_1 = (p_1 - w)Q_2 \end{array} \right. \end{array} \right. \quad (26)$$

Lemma 4. The NE values of p_1 and p_2 are:

$$p_1^* = \frac{2\beta(w\beta + \theta\lambda + \gamma p_d + \alpha_2) + \gamma(e^g k + \theta\lambda + \beta(w + c_t) + \gamma p_d + \alpha_3)}{4\beta^2 - \gamma^2} \quad (27)$$

$$p_2^* = \frac{(e^g k + \beta c_t + \alpha_3)2\beta + (2\beta + \gamma)((w\beta + \theta\lambda) + \gamma p_d) + \gamma\alpha_2}{4\beta^2 - \gamma^2} \quad (28)$$

Proof. To obtain the equilibrium prices, the following equation system is solved:

$$\left\{ \begin{array}{l} \frac{d\pi_1}{dp_1} = 0 \rightarrow \beta(w - 2p_1) + \theta\lambda + \gamma(p_2 + p_d) + \alpha_2 = 0 \\ \frac{d\pi_2}{dp_2} = 0 \rightarrow e^g k + \theta\lambda + \beta(c_t + w - 2p_2) + \gamma(p_1 + p_d) + \alpha_3 = 0 \end{array} \right. \quad (29)$$

$$(30)$$

Lemma 5. The equilibrium value of c_t is:

$$c_t^* = \frac{B_1 + \xi B_2 - (2\beta + \gamma)(w\beta - w\gamma - \theta\lambda - \gamma p_d)}{2B_2} \quad (31)$$

Proof. c_t^* is calculated by solving Eq. (32):

$$\frac{d\pi_{3pl}}{dc_t} = 0 \rightarrow \frac{\beta((-(\beta - \gamma)w - \theta\lambda) + \gamma p_d)(2\beta + \gamma) + (\xi - 2c_t)(B_2) + B_1}{(2\beta - \gamma)(2\beta + \gamma)} = 0 \quad (32)$$

Note. In the whole paper, B_i is the i^{th} change of the variables.

Lemma 6. The EVs of the wholesale price, product price in the direct channel, and greenness degree are:

$$\theta^* = \varphi B_{14} + B_{15} \quad (33)$$

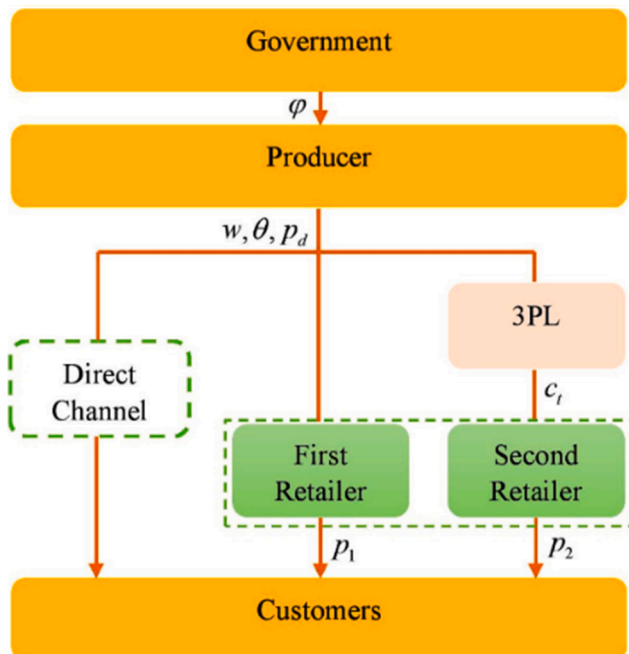


Fig. 2. The general scheme of the game in Problem II.

$$w^* = \varphi B_{16} + B_{17} \quad (34)$$

$$p_d^* = \varphi B_{18} + B_{19} \quad (35)$$

Proof. With regard to the Stackelberg competition in each SC and the equilibrium values obtained for the retailers and the 3PL companies, the following set of equations is solved to reach the EVs for the producer.

$$\begin{cases} \frac{d\pi_M}{d\theta} = 0 \rightarrow -\eta\theta + \varphi B_3 + wB_4 + B_6 + B_5 p_d = 0 \end{cases} \quad (36)$$

$$\begin{cases} \frac{d\pi_M}{dp_d} = 0 \rightarrow \theta B_5 + wB_7 + \varphi B_8 + B_{10} + B_9 p_d = 0 \end{cases} \quad (37)$$

$$\begin{cases} \frac{d\pi_M}{dw} = 0 \rightarrow \theta B_4 + wB_{11} + \varphi B_{12} + B_{13} + B_7 p_d = 0 \end{cases} \quad (38)$$

3.3.3. Problem III: A set of two producers (green and non-green), one 3PL, and two retailers

In this problem, two rival SCs, including a GSC and an N-GSC, are taken into consideration. Each SC has two distribution channels (i.e., direct and indirect channels). A 3PL company provides services between the first producer and the first retailer in the first SC. The first producer produces green products, while the second one produces non-green products. As in problems I and II, the government supervises the activities of the SCs and assigns specific levels of tariffs to the producers. The schematic diagram of Problem III is shown in Fig. 3.

3.3.3.1. The demand functions. The demand objective functions for each SC and in each channel are shown in Eqs. (39)–(42):

$$Q_1 = \alpha_1 - \beta p_{d1} + \gamma(p_1 + p_2 + p_{d2}) + \lambda_1 \theta \quad (39)$$

$$Q_2 = \alpha_2 - \beta p_1 + \gamma(p_{d1} + p_2 + p_{d2}) + \lambda_1 \theta + A^{3pl} \quad (40)$$

$$Q_3 = \alpha_3 - \beta p_2 + \gamma(p_{d1} + p_1 + p_{d2}) - \lambda_2 \theta \quad (41)$$

$$Q_4 = \alpha_4 - \beta p_{d2} + \gamma(p_1 + p_2 + p_{d1}) - \lambda_2 \theta \quad (42)$$

To demonstrate the superiority of the green product over the non-green one, function $\lambda_2 \theta$ has been added to the demand function of the third and the fourth channels of the second producer (Liu, Zhang, Zhu, & Chu, 2017).

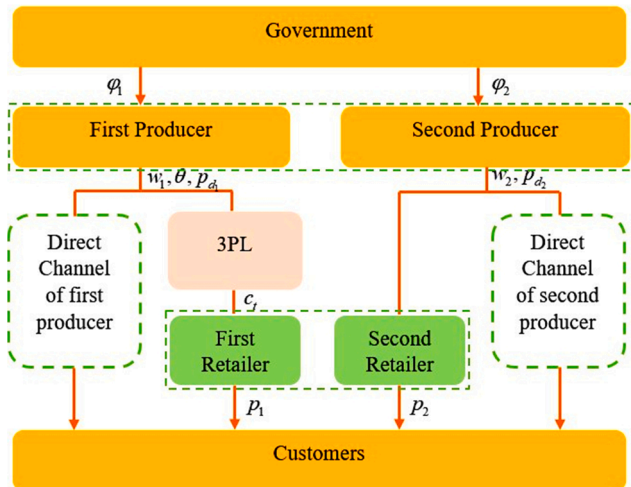


Fig. 3. The general scheme of the game in Problem III.

3.3.3.2. The profit functions for each player. The first retailer has a Q_2 demand function which sells the products at retail prices p_1 . In addition, it buys the products from the first producer at wholesale prices w_1 . The second retailer has a Q_3 demand function that sells the products at retail price p_2 and buys them from the second producer at wholesale price w_2 . It is assumed that the 3PL company only provides services in the first SC and only for the first retailer. Therefore, the profit functions for the retailers are:

$$\pi_1 = (p_1 - w_1 - c_i)Q_2 \quad (43)$$

$$\pi_2 = (p_2 - w_2)Q_3 \quad (44)$$

Also, the profit function of the 3PL company is:

$$\pi_{3pl} = (c_i - \xi)Q_2 \quad (45)$$

In this study, it is assumed that, in any channel without a 3PL company, it is the producers that pay the shipping costs. The producers' profits are calculated as follows:

$$\pi_{M1} = (p_{d1} - f_1 + \varphi_1 - \chi_1)Q_1 + (w_1 - f_1 + \varphi_1)Q_2 - \eta \frac{\theta^2}{2} \quad (46)$$

$$\pi_{M2} = (w_2 - f_2 + \varphi_2 - \chi_2)Q_3 + (p_{d2} - f_2 + \varphi_2 - \chi_2)Q_4 \quad (47)$$

3.3.3.3. The equilibrium values in Problem III. In Problem III, in addition to retailers, there is a Nash competition among producers. The decision-making structure and the solution sequences for the third game are as follows:

$$\left\{ \begin{array}{l} \text{Max } \pi_G \\ \text{Max } \pi_{M1} = (p_{d1} - f_1 + \varphi_1 - \chi_1)Q_1 + (w_1 - f_1 + \varphi_1)Q_2 - \eta \frac{\theta^2}{2} \\ \text{Max } \pi_{M2} = (p_{d2} - f_2 + \varphi_2 - \chi_2)Q_4 + (w_2 - f_2 + \varphi_2 - \chi_2)Q_3 \\ \text{Max } \pi_{3pl} = (c_i - \xi)Q_2 \\ \left\{ \begin{array}{l} \text{Max } \pi_2 = (p_2 - w_2)Q_3 \\ \text{Max } \pi_1 = (p_1 - w_1 - c_i)Q_2 \end{array} \right. \end{array} \right. \quad (48)$$

Lemma 7. The optimal retail prices are:

$$p_1^* = - \frac{\left(-\gamma(\alpha_3 + w_2\beta + (p_{d1} + p_{d2})\gamma - \theta\lambda_2) - 2\beta(\alpha_2 + ke^g + (c_i + w_1)\beta + (p_{d1} + p_{d2})\gamma + \theta\lambda_1) \right)}{4\beta^2 - \gamma^2} \quad (49)$$

$$p_2^* = \frac{\left(2\alpha_3\beta + 2w_2\beta^2 + \alpha_2\gamma + ke^g\gamma + c_i\beta\gamma + 2p_{d1}\beta\gamma + w_1\beta\gamma + 2p_{d2}\beta\gamma + p_{d1}\gamma^2 + p_{d2}\gamma^2 - 2\beta\theta\lambda_2 + \gamma\theta\lambda_1 \right)}{4\beta^2 - \gamma^2} \quad (50)$$

Proof. To find the EVs of p_1 and p_2 , the following set of equations is solved:

$$\begin{cases} \frac{d\pi_1}{dp_1} = 0 \rightarrow \alpha_2 + ke^g + (c_i - 2p_1 + w_1)\beta + (p_2 + p_{d1} + p_{d2})\gamma + \theta\lambda_1 = 0 \end{cases} \quad (51)$$

$$\begin{cases} \frac{d\pi_2}{dp_2} = 0 \rightarrow \alpha_3 - 2p_2\beta + w_2\beta + (p_1 + p_{d1} + p_{d2})\gamma - \theta\lambda_2 = 0 \end{cases} \quad (52)$$

Lemma 8. The equilibrium amount of c_i is:

$$c_i^* = - \frac{w_2D_1 + w_1D_2 + (p_{d1} + p_{d2})D_3 + \theta D_4 + D_5}{2D_2} \quad (53)$$

Proof. The first-order derivative for the profit function of the 3PL company is calculated as follows:

$$\frac{d\pi_{3pl}}{dc_i} = 0 \rightarrow \frac{\beta \left(2\alpha_2\beta + 2ke^s\beta - 4c_i\beta^2 - 2w_1\beta^2 + \alpha_3\gamma + 2p_{d_1}\beta\gamma + w_2\beta\gamma + 2p_{d_2}\beta\gamma \right)}{4\beta^2 - \gamma^2} = 0 \quad (54)$$

As Eq. (54) is solved, the equilibrium value of the decision variables is obtained.

Note. In the whole paper, D_i is the i^{th} change of the variables.

Lemma 9. The EVs for the decision variables of the producers are as follows:

$$\theta^* = D_{34} + D_{33}\varphi_1 + D_{32}\varphi_2 \quad (55)$$

$$p_{d_1}^* = D_{37} + D_{36}\varphi_1 + D_{35}\varphi_2 \quad (56)$$

$$w_1^* = D_{43} + D_{42}\varphi_1 + D_{41}\varphi_2 \quad (57)$$

$$w_2^* = D_{46} + D_{45}\varphi_1 + D_{44}\varphi_2 \quad (58)$$

$$p_{d_2}^* = D_{40} + D_{39}\varphi_1 + D_{38}\varphi_2 \quad (59)$$

Proof. To obtain the EVs of $(\theta, w_1, w_2, p_{d_1}, p_{d_2})$, the following set of equations must be solved:

$$\begin{cases} \frac{d\pi_{M_1}}{d\theta} = 0 \rightarrow -\eta\theta + D_{28}p_{d_1} + D_{14}w_1 + \frac{1}{2}D_8\varphi_1 + \frac{1}{2}D_9 = 0 \quad (60) \\ \frac{d\pi_{M_1}}{dw_1} = 0 \rightarrow D_2w_1 + D_{11}\varphi_1 + D_{29}\theta + D_{30}p_{d_2} + D_{31}p_{d_1} + D_{32}w_2 + D_{15} = 0 \quad (61) \\ \frac{d\pi_{M_1}}{dp_{d_1}} = 0 \rightarrow D_6\theta + D_{13}w_1 + D_{16}w_2 + D_{17}p_{d_2} + D_{18}p_{d_1} + D_{19}\varphi_1 + D_{20} = 0 \quad (62) \\ \frac{d\pi_{M_2}}{dw_2} = 0 \rightarrow \frac{D_3}{2}w_1 + D_{17}p_{d_1} + D_{18}p_{d_2} + D_{23}w_2 + D_{26}\theta + D_{34}\varphi_2 + D_{33} = 0 \quad (63) \\ \frac{d\pi_{M_2}}{dp_{d_2}} = 0 \rightarrow \frac{D_1}{2}w_1 + D_{22}p_{d_1} + D_{23}p_{d_2} + D_{24}\theta + D_{35}\varphi_2 + D_{36}w_2 + D_{37} = 0 \quad (64) \end{cases}$$

4. Government's model

In this study, the government is considered as the leader of all the presented games. It has an important role in managing and controlling structures and in guiding companies and manufacturers to be beneficial to the people and the state. By monitoring the activities of the members of SCs, the government can affect their behavior using different policies and tools. In this study, it is also assumed that the government influences SCs through financial intervention. It monitors the producers' activities and makes decision about the tariffs (taxes/subsidies) assigned to each producer. In such a way, the producers will pay taxes or subsidies according to the amount of their production. To obtain the optimal level of tariffs, one of the two scenarios may be used by the government.

4.1. The first scenario

In the first scenario, it is assumed that the government's goal is to maximize its profit from the SCs' activities. In this example, the government only counts on the upper bound to control the emissions released by the producers. Based on this assumption, the model proposed for the government in the first scenario (GS1) can be presented as Eq. (65).

$$\begin{aligned} \text{Max } \pi_G = & \sum_{i=1}^{|I|} (-\varphi_i)Q_{M_i} \\ \text{S.t. } & \pi_{M_i} \geq RUM_i \quad \forall i \in I \\ & \pi_{3pl_r} \geq RUT_r \quad \forall r \in R \\ & \pi_j \geq RU_j \quad \forall j \in J \end{aligned} \quad (65)$$

$$\sum_{l=1}^{|L|} \sum_{i=1}^{|I|} CP_l Q_{M_i} + \sum_{s \in (S-Y)} \zeta Q_s + \sum_{y \in Y} \sigma \zeta Q_y \leq MP_G$$

$RUM_i \geq 0, RU_j \geq 0, RUT_r \geq 0, MP_G \geq 0, \varphi_i$ is free in sign

The government's profit is defined as an objective function. The first to the third constraints refer to the minimum profits set by the producers, the 3PL, and the retailers respectively. It is logical to assume that a player will not stay in the game unless it achieves a predetermined minimum level of profit. The fourth constraint represents the maximum permissible amount of the pollution released by the producer authorized by the government.

4.2. The second scenario

The second scenario (GS2) assumes that the government's goal is to minimize the polluting emissions caused by the production activities, despite assuring a lower level for its revenue. Based on this explanation, the government's model in the second scenario is as follows:

$$\begin{aligned} \text{min } \pi_G = & \sum_{l=1}^{|L|} \sum_{i=1}^{|I|} CP_l Q_{M_i} + \sum_{s \in (S-Y)} \zeta Q_s + \sum_{y \in Y} \sigma \zeta Q_y \\ \text{S.t. } & \pi_{M_i} \geq RUM_i \quad \forall i \in I \\ & \pi_{3pl_r} \geq RUT_r \quad \forall r \in R \\ & \pi_j \geq RU_j \quad \forall j \in J \\ & \sum_{i=1}^{|I|} (-\varphi_i)Q_{M_i} \geq RUG \\ & RUM_i \geq 0, RU_j \geq 0, RUT_r \geq 0, MP_G \geq 0, \varphi_i \text{ is free in sign} \end{aligned} \quad (66)$$

5. Numerical examples and parametric sensitivity analysis

In this section, some numerical examples are solved, and the results are analyzed to show how the proposed models deal with real-world problems. All the parameter values are set according to the numerical examples in the literature, the problem conditions, and the conditions obtained in the problem-solution procedures provided in Appendix 1, 2, and 3. To this end, three references including Gao et al. (2016), Jamali and Rasti-Barzoki (2019), and Liu et al. (2020) have been considered. It should be noted the numbers are not exactly repeated, but the exact patterns have been followed to find the most suitable values for these problems. Because, there are significant differences between the structures of the discussed problems in this study and the ones in the literature; hence, it's not possible to use the same values. Table 2, Table 3, and Table 4 show the values for the parameters in Problems I, II, and III respectively.

Once the parameter values are set in all the problems, optimal solutions are obtained for the decision and profit variables of the SC members (as shown in Tables 5, 6 and 7).

Table 2

The values of the parameters in Problem I.

Parameter	Value	Parameter	Value
(α_1, α_2)	(2400, 1800)	f	800
$(\beta, \gamma, \lambda, \eta)$	(2, 0.5, 0.7, 1)	(k, e^s)	(0.2, 800)
(ξ, χ)	(140, 400)	(ζ, σ)	(0.3, 0.4)

Table 3

The values of the parameters in Problem II.

Parameter	Value	Parameter	Value
$(\alpha_1, \alpha_2, \alpha_3)$	(2000,1800,2200)	f	800
(β, γ, λ)	(2,0.2,0.03)	(ξ, χ_1, χ_2)	(140,400,400)
(k, e^g)	(0.2,800)	$(\eta, \varsigma, \sigma)$	(1,0.3,0.4)

Table 4

The values of the parameters in Problem III.

Parameter	Value	Parameter	Value
$(\alpha_1, \alpha_2, \alpha_3, \alpha_4)$	(2200,2600,2000,2200)	(f_1, f_2)	(360,350)
$(\beta, \gamma, \lambda_1, \lambda_2)$	(3,0.1,0.08,0.07)	(ξ, χ_1, χ_2)	(70,220,230)
(k, e^g)	(0.2,800)	$(\eta, \varsigma, \sigma)$	(3,0.3,0.4)

Table 5

The decision values of the government.

Variables	Value		
	Problem (I) (GS1, GS2)	Problem (II) (GS1, GS2)	Problem (III) (GS1, GS2)
φ_1	(−88.860,1.798)	(48.085,164.581)	(−152.008, −223.156)
φ_2	–	–	(−49.206, −50.802)

Table 6

The equilibrium values for the SC members' decision variables.

Variables	Value		
	Problem (I) (GS1, GS2)	Problem (II) (GS1, GS2)	Problem (III) (GS1, GS2)
p_1	(1575.47,1572.38)	(1135.29,1101.98)	(942.592,952.437)
p_2	(1293.22,1282.86)	(1374.01,1340.33)	(719.02,720.616)
p_{d_1}	–	(1205.54,1147.32)	(773.342,808.942)
p_{d_2}	–	–	(722.41,724.006)
θ	(70.6141,103.832)	(4.05067,7.43509)	(2.47179,1.2803)
w_1	(1273.86,1236.28)	(1113.29,1055.08)	(718.665,754.264)
w_2	–	–	(690.152,691.748)
c_t	(248.314,271.429)	(220.544,245.144)	(172.628,155.456)

Table 7

The equilibrium profit values for the SC members.

Variables	Value		
	Problem (I) (GS1, GS2)	Problem (II) (GS1, GS2)	Problem (III) (GS1, GS2)
π_1	(5681.21,8364.83)	(1000,4399.13)	(7894.94,5474.02)
π_2	(999.997,4338.79)	(3227.42,5190.94)	(2499.99,2499.99)
π_{3pl}	(11545.7,16999.5)	(6471.06,13607.8)	(15794.3,10951.1)
π_{M_1}	(37875.3,54819.8)	(32177.1,77842.2)	(36696.2,22000)
π_{M_2}	–	–	(31011,31010.9)
π_G	(13445.942,87.967)	(−10388.098,567.338)	(59264.642,251.003)

5.1. Effect of φ and k on the decision variables and the profit functions in Problem I

Increasing the greenness degree of the product requires investment in equipment and production systems. On the other hand, new investments increase production costs and, as a result, the final price of the product is increased. A high price may reduce the product demand in the target market. Therefore, producers are usually not interested in producing green products or increasing the greenness degree of their pro-

duction. Some sensitivity analyses are reported in Fig. 4 to show how equilibrium values react to the changes in various key variables in Problem I. As seen in Fig. 4-a, the greenness degree of the product is directly related to the 3PL advantage factor (k). In addition, as the value of k changes, the value of θ changes in the same direction too. Given Fig. 4-b, the effects of government tariffs on the retailers' profit can be analyzed in three different slots. In slot I, the profit of the second retailer is higher than that of the first retailer. However, in the second interval, i. e., $[-300,120]$, the profit of the first retailer is higher than that of the second retailer. As the tariff is increased in the third slot, the profit of the second retailer exceeds that of the first retailer again. The growth of the second retailer's profit is explained through the analysis of the demand functions and by the equation of the equilibrium retail price. Its surpassing the profit of the first retailer is due to the faster decrease of the second retailer's price than the first retailer's. Consequently, with the growth of tariffs, the demand and the profit also increase for the second retailer.

In Problem I, there is only one producer selling the products at the same wholesale price in both channels; therefore, it is logical for the customer to buy from the channel offering a lower price. Fig. 4-c and -d show that the profits of the producer and the 3PL have a nonlinear relationship with the tariffs. Also, Fig. 4-e shows that an increase in k causes an increase in the first retailer's profit. The sensitivity of the first retailer's profit to k is more than that of the second one. According to Fig. 4-f, as the value of k increases, the profit of the producer increases nonlinearly. An important result of this study can be taken from this figure; the more public awareness of the importance of 3PL and green activities in SCs, the more the demand/profit through 3PL channels. Retailers' profits increase in this process too. The parameters k and φ are of great influence in SCs. Fig. 4-g shows that, when the 3PL has the most profits, k and φ are at their highest. Through the analysis of the demand and profit equations, both parameters have been found to have a direct linear relationship with the demand and profitability of the first retailer and the 3PL. Hence, an increase in both parameters can cause a significant growth in the 3PL profit. By investing in the programs which raise the public awareness of sustainability, green products and 3PLs, the government can, indeed, affect the cooperation between SCs and 3PLs and enhance the sustainability of SCs significantly.

Corollary 1. A reduction in product prices can have a significant impact on the increase of product demands. Moreover, an increase in the demand can be due to improved brand popularity as a result of greener production.

Corollary 2. The cooperation of the 3PL company and the producer can cause higher-level sustainability in SC.

5.2. The effects of φ and k on decision variables and profit functions in Problem II

The sensitivity analysis of how k affects the greenness degree of the product (Fig. 5-a) shows that these two parameters have a direct linear relationship. Therefore, any policy leading to an increase in k can result in a rise in the greenness degree and sustainable activities. Due to the implementation of special strategies, the transportation activities done by 3PL companies are more efficient than the regular distribution processes conducted by producers. Hence, the level of pollutant emissions through transportation in the 3PL channel is significantly less than that in other channels. In this regard, providing the public with the awareness of how to cooperate with 3PL companies can be an eco-friendly strategy, leading to a rise in the demand through the 3PL channel. The results show that the prices are higher in the 3PL channel than in other channels. Therefore, the consumer expects 3PL companies to perform more efficiently, such as providing an eco-friendlier transportation fleet. In the interval $[-450, -150]$, there is the relationship $\pi_1 > \pi_2$ established. If the government's goal is to increase its revenue through taxation, the green producer will no longer be willing to cooperate with the 3PL, which will increase shipping through other channels. As a

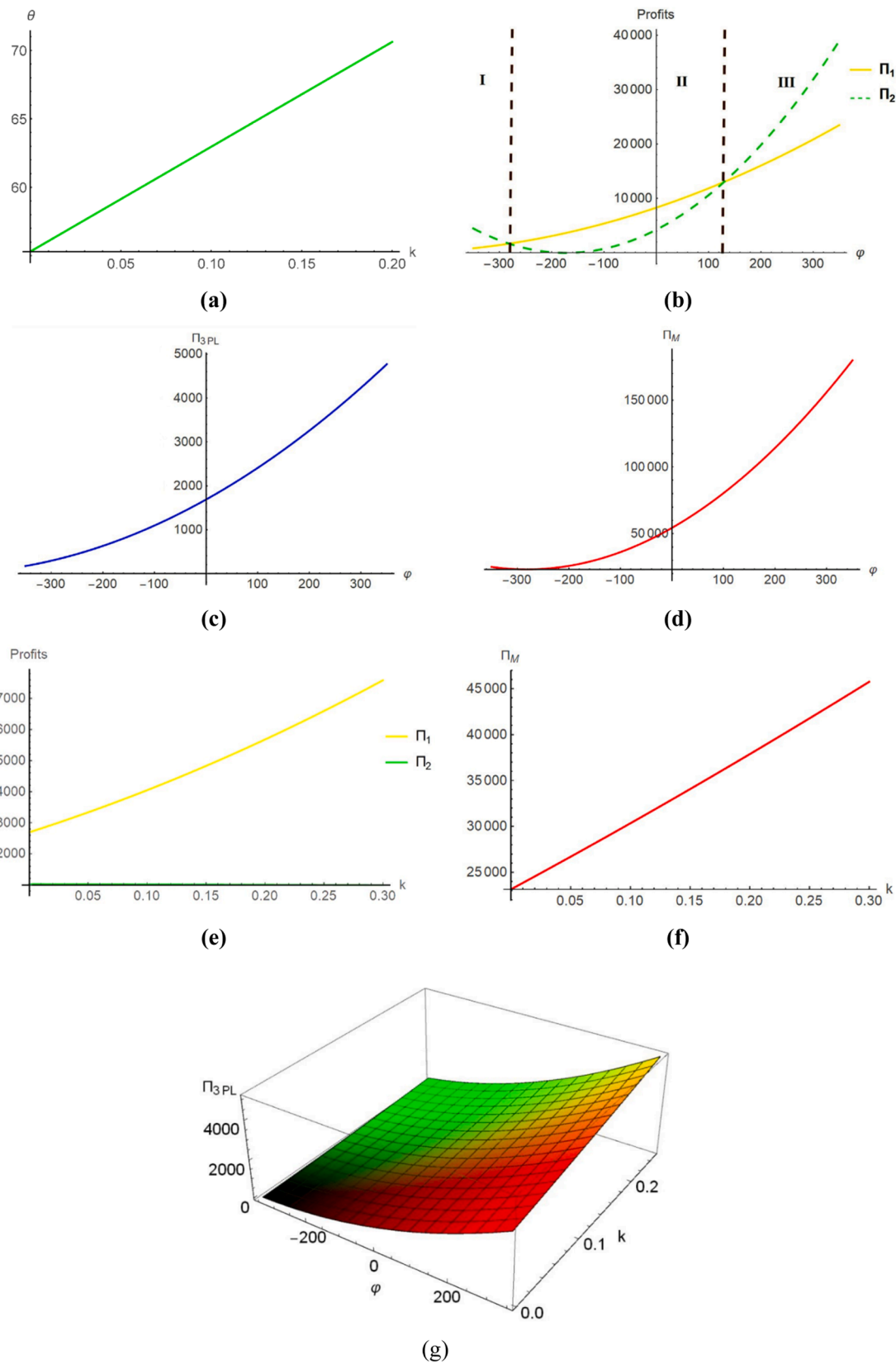


Fig. 4. Sensitivity analysis of equilibrium values in Problem I.

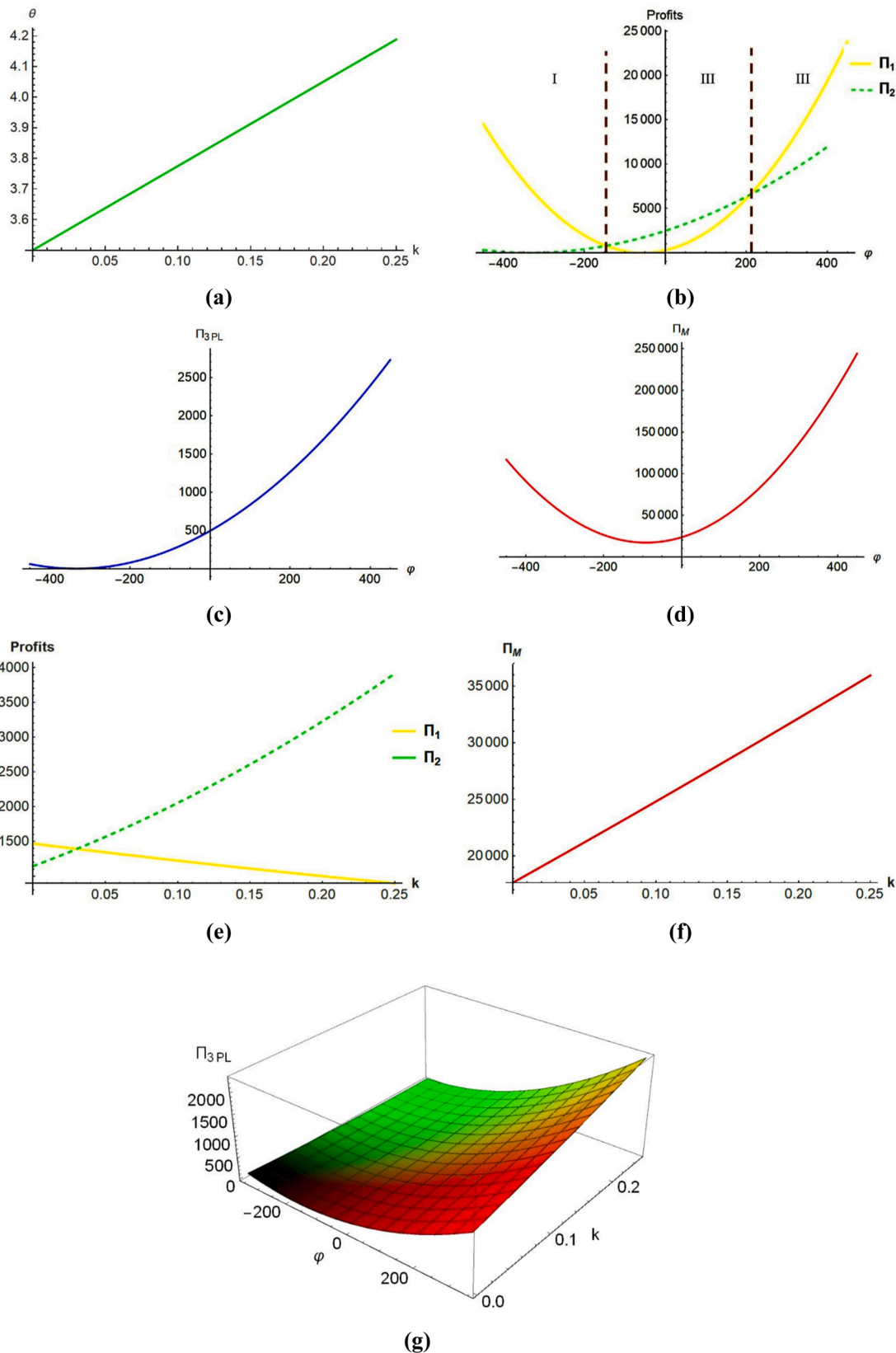


Fig. 5. Sensitivity analysis of equilibrium values in Problem II.

result, there will be more emissions through transportation and non-green production activities. When the government's strategy shifts towards raising the public awareness of the benefits of cooperation with 3PL companies, the demand from 3PL channels will increase. The

retailer profits of the 3PL channel will, thus, increase too, and the $\pi_2 > \pi_1$ relationship will be established in the interval $[-150, 210]$. Obviously, this occurs due to the decrease in the demand of regular channels, as compared to the 3PL channel. The third slot shows that the tendency of

the market to use the product distributed through the 3PL channel gradually gets back to normal. This is due to the consumer's response to the rising prices in the 3PL channel; the existence of just one producer and one type of product with an increased price makes the consumers increasingly focus on the economic, rather than environmental, aspect of the product. If the goal of the government and the producer is to increase the sustainability of the SC, the producer and the first retailer should reduce the price difference between the regular and 3PL channels. Fig. 5-c and -e show that there is a nonlinear relationship between φ and the profits of the producer and the 3PL. As φ increases, the greenness degree of the product increases too. The producer can raise the greenness degree of the product by investing in green production systems, which will lead to a financial burden. To encourage investment in green production systems, the government should give financial aids to producers. As Fig. 5-d suggests, an increase in the subsidies leads to an increase in the profit of the producer. Moreover, as shown in Fig. 5-e, when the advantage factor of the 3PL is enhanced in the channel (k), the profit of the second retailer rises to become higher than the first retailer's profit in area II. Promoted consumer awareness of the advantage of cooperation with 3PL companies in distribution channels will induce the growth of demand. An increased number of products distributed in a 3PL channel, compared to other regular channels, will lead to less emission of pollutants. In addition, as shown in Fig. 6-f, it increases the profit of the producer. In fact, the figure refers to a direct and linear relationship between the producer's profit and k . As a result, investments to raise the public awareness of the benefits of 3PL companies can increase the sustainability of SCs. According to Fig. 5-g, an increase in k and the government's tariffs can expand the profit margin for 3PL companies. Based on the explanations given in the previous sections and the analysis of the figures, it is found that the parameter k has a direct linear relationship with the greenness degree, and the greenness degree is related in the same direction with tariffs. It can, thus, be concluded that the maximum profit of a 3PL company is achieved when both of these parameters are at their maximum values.

Corollary 3. *Cooperation with 3PL companies can have a positive effect on the profits of producers and retailers.*

Corollary 4. *If the tax rate is raised, the producer will be reluctant to cooperate with 3PL companies and the sustainability of SCs will decrease.*

5.3. Effects of tariffs (φ_1 , φ_2) and k on the decision variables and the profit functions in Problem III

Fig. 6-a, just as in the first two games, demonstrates that the advantage factor of the 3PL (k) has a direct linear relationship with the greenness degree. In addition, Fig. 6-d shows that the profit of the first producer is increased when the tariff is raised. It can be concluded that the profit of the first producer depends more on the amount of its own tariff than on the opponent's tariff. The profit of the first producer will be on the top when the government imposes the maximum tax on the second producer and gives the maximum subsidy to the first producer. The government may adopt an indifference strategy (i.e., neither taxing nor subsidizing) for the green producer and a penalizing strategy (i.e., taxing) for the second producer (i.e., for non-green products). In this case, the second producer will react to those strategies by gradually taking one of two measures, either developing the infrastructure needed to produce green products or decreasing the production level. Both reactions will lead to higher sustainability in SCs.

If the government's strategy is to increase its profits through taxation, as Fig. 6-b shows, the profit of both retailers will decrease. However, the profit objective function of the first retailer is more sensitive to the reduction of the tariffs than that of the second retailer. Hence, the government's strategy to deal with producers is a critical factor in the sustainability of SCs. The responses of the first producer and the 3PL to tariff changes are quite similar to the retailer's behavior in the 3PL channel (Fig. 6-c and -d). From Fig. 6-e, it can be concluded that there is

a linear relationship between k and the profits of the first and the second retailers. An increase in the value of k will, however, increase the profit of the first retailer significantly more than the second retailer's profit. A raise in the k value also causes an increase in both producers' profit (Fig. 6-g).

The government should encourage cooperation with 3PL companies by giving financial supports to producers (Fig. 6-c). The higher the k value and the tariff allocated to the first producer (φ_1), the greater the profit value of the 3PL. The effect of factor k on the 3PL profit is more significant than that of factor φ_1 . As Fig. 6-f shows, if the government undertakes the profit-maximization scenario, an increase in k can lead to a raise in the 3PL's profit.

Corollary 5. *There is a direct and nonlinear relationship between the value of k and the amount of the producer's and retailer's profits in the 3PL channel.*

Corollary 6. *Imposing taxes on non-green producers and giving subsidies to green producers will increase the sustainability of SCs.*

5.4. Managerial insights

Evaluating the proposed models and analyzing the obtained results for the numerical examples can provide some important managerial insights as follows:

- Raising public awareness can increase the demand for green producers and the tendency for the cooperation of producers and 3PLs. This results in the improved sustainability of SCs. Hence, the governments and other non-governmental organizations are encouraged to invest in all strategies that can raise public knowledge and awareness about sustainability and sustainable development. This can be done through the media, social networks, school books, etc.
- There is a direct relationship between the profit of green producers and the public awareness factor (k). In addition, the profit of 3PL companies is more sensitive to k than to tariffs. Hence, investing in public awareness not only improves the sustainability of the SCs but also increases the profit of the players. This strategy can be called a win-win strategy.
- The results showed that in the case of cooperating with 3PL companies the SC will perform more sustainable performance compared to the case of do not have 3PLs in the SC. According to this finding, governments can encourage producers to cooperate with 3PLs by making supportive financial and non-financial policies. Taking fewer taxes, giving subsidies, or assigning more market share to the producers who cooperate with the 3PL can be some of the possible supportive policies.
- Tariffs are one of the most effective tools to control the SCs' members' activities. Governments can monitor the activities of SCs and affect their sustainability by financial intervention, including taxation and subsidization. The results confirmed that both taking taxes from non-green players and giving subsidies to the green players will persuade players to move toward sustainable activities. It should be noted that it's important to know which level of the subsidies must be assigned to the green producers and/or how much taxes must be taken from the non-green producers to achieve the sustainability goals. Based on the results, it can be seen that merely subsidizing green players and collecting taxes from non-green players are not enough, and in some cases where the amounts of the assigned subsidies are not big enough, even taking taxes from the non-green players will not encourage them to apply green policies. This is because of the more expensive production process of the green products. As a result, this leads to a high sell price for these products that can affect the market share of the producer and decrease their utility.

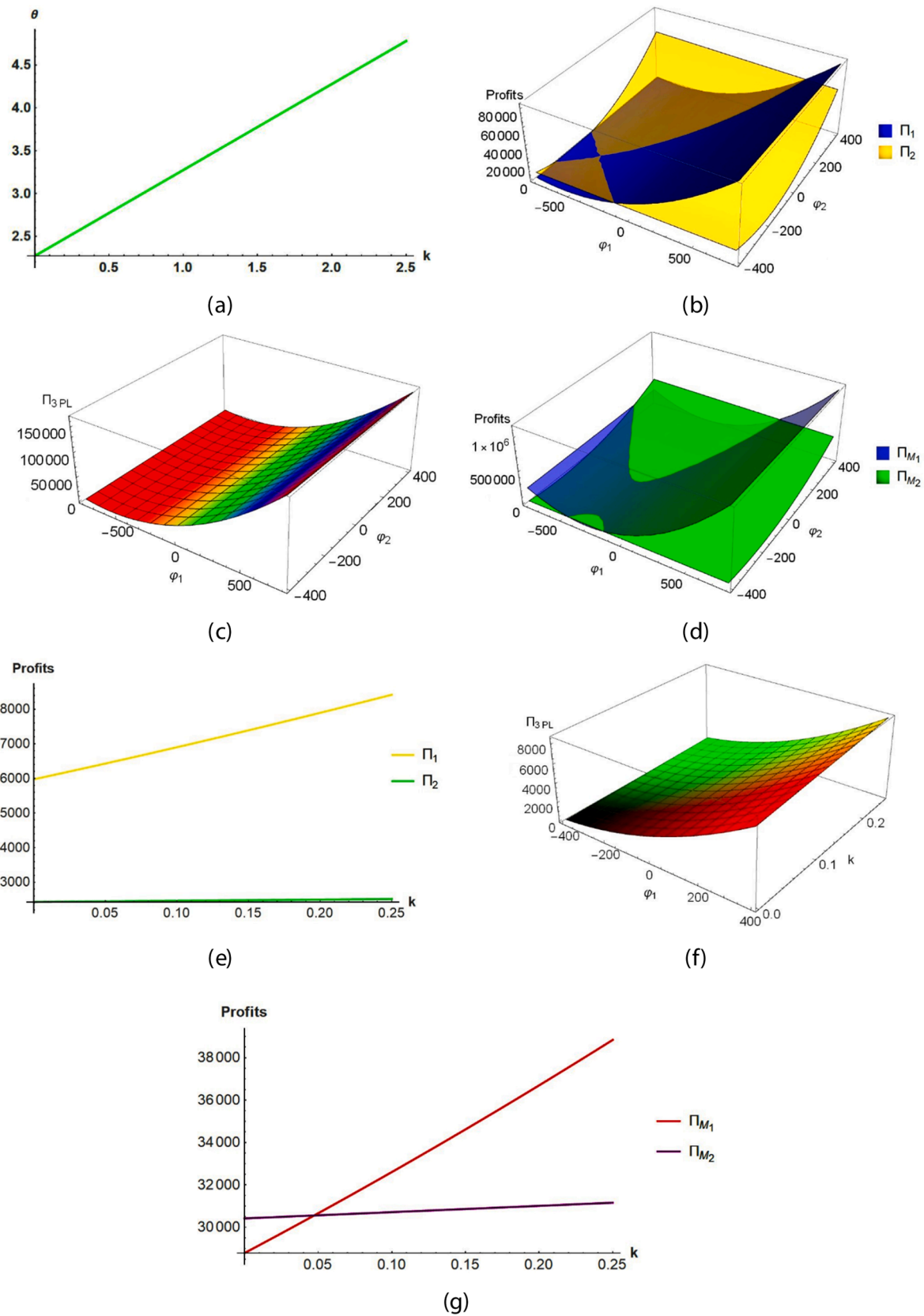


Fig. 6. Sensitivity analysis of the equilibrium values in Problem III.

6. Conclusion and suggestions for future research

This study is the investigation of the impact of 3PL companies, government financial interventions, and public awareness on the sustainability of SCs. Three different problems are modeled based on the market and the SC structures, and equilibrium strategies and values are postulated using the GT method. To the best of the authors' knowledge, this study claims to be one of the most comprehensive studies in the field. For the first and the second problems, it is assumed that there is only one producer who produces green products. In the next problems, however, two producers are considered in the games, a green producer and a non-green producer. In all the problems, it is assumed that the government is the leader of the games and influences the SCs, particularly the producers' behavior, through the imposition of tariffs and taxes or giving subsidies. Some numerical examples are also presented and solved by the proposed models.

The results show that 3PL companies and public awareness can play key roles to enhance SC sustainability. However, it is indicated that the presence of 3PL companies can increase costs for producers and, in some cases, for buyers. The government can also have direct impacts on the profit of SC members and the sustainability of SCs by taxing and subsidizing producers. In all the three analyzed problems, the advantage factor of 3PL in the SCs (k) and the level of the government tariffs (φ) have proved to be linearly related to the greenness degree of the products.

In particular, the results showed that increasing public awareness toward sustainability can make the profit of green producers up to 400% higher than non-green producers. This difference even can reach 800% for the green retailers. Although the results showed that tariffs will be

effective tools, it can be seen that at least for the given examples the difference between the profits of the green and non-green producers under the imposed tariffs will be up to 150%. It means that raising public awareness will lead to higher profit for the green producers and equivalently higher sustainability in the SC's members' activities compared to imposing tariffs.

Although the current study makes important contributions, there are still some issues to explore in future studies. First, while this research assumes all the parameters and the variables in a deterministic form, future studies can do modelling in uncertainty conditions. Second, other players in a SC, such as suppliers, can be included in games. Developing single- or multi-population evolutionary GT models to study the long-term behavior of players is a challenging but interesting task. Considering retailers as the leader of the game or monitoring their activities by the government would be another interesting subject for future research. Finally, real-case studies and those like the one reported in this paper are recommended to be conducted for CLSCs.

Funding

The authors would like to express their appreciation to the Iran National Science Foundation (INSF) (Grant No. 93042256) for the financial support of this study. This support is gratefully acknowledged.

CRedit authorship contribution statement

Ali Mahmoudi: Data curation, Writing - original draft, Software. **Kannan Govindan:** Conceptualization, Methodology. **Davood Shish-e-bori:** Supervision. **Reza Mahmoudi:** Software, Validation.

Appendix A. The concavity of profit functions in Problem I

Note. To investigate the optimization conditions, the second derivative condition and the Hessian matrix are used for single-variable and multivariable functions respectively. For single-variable functions, the first-order derivative must be negative. For multivariable functions, the Hessian matrix must be negative-definite.

The second derivative condition for the retailers' profit function is:

$$\frac{d^2\pi_1}{dp_1^2} = \frac{d^2\pi_2}{dp_2^2} = -2\beta < 0 \quad (\text{A.1})$$

Since β is a positive parameter, the second derivative is negative for both retailers.

Also, the second derivative condition for the 3PL's profit function is as follows:

$$\frac{d^2\pi_{3pl}}{dc_i^2} = \frac{-4\beta^3 + 2\beta\gamma^2}{4\beta^2 - \gamma^2} < 0 \quad (\text{A.2})$$

Since $\beta > \gamma$, it is clear that Eq. (A.2) is negative.

The Hessian matrix for the producer's profit function is obtained as follows:

$$H_1 = \begin{pmatrix} \frac{\partial^2\pi_M}{\partial\theta^2} & \frac{\partial^2\pi_M}{\partial\theta\partial w} \\ \frac{\partial^2\pi_M}{\partial w\partial\theta} & \frac{\partial^2\pi_M}{\partial w^2} \end{pmatrix} = \begin{pmatrix} -\eta & \frac{\beta(6\beta^2 + \beta\gamma - 3\gamma^2)\lambda}{2(2\beta - \gamma)(2\beta^2 - \gamma^2)} \\ \frac{\beta(6\beta^2 + \beta\gamma - 3\gamma^2)\lambda}{2(2\beta - \gamma)(2\beta^2 - \gamma^2)} & \beta\left(-3 - \frac{2\beta}{-2\beta + \gamma} + \frac{\beta^2}{2\beta^2 - \gamma^2}\right) \end{pmatrix} \quad (\text{A.3})$$

H_1 matrix will be negative-definite if:

$$\begin{cases} -\eta < 0 \\ \text{and} \\ |H_1| > 0 \rightarrow \frac{\left(\beta(6\beta^2 + \beta\gamma - 3\gamma^2)\left(4(4\beta^4 - 6\beta^3\gamma + 3\beta\gamma^3 - \gamma^4)\eta\right)\right)}{4(-2\beta + \gamma)^2(-2\beta^2 + \gamma^2)^2} > 0 \end{cases} \quad (\text{A.4}) \quad (\text{A.5})$$

Since $\eta > 0$, the condition $-\eta < 0$ is always satisfied. To have $|H_1| > 0$, the following condition must be established:

$$\eta > \frac{\beta(6\beta^2 + \beta\gamma - 3\gamma^2)\lambda^2}{4(4\beta^4 - 6\beta^3\gamma + 3\beta\gamma^3 - \gamma^4)} \quad (\text{A.6})$$

Appendix B. The concavity of profit functions in Problem II

The second derivative condition for the profit of retailers is as follows:

$$\frac{d^2\pi_1}{dp_1^2} = \frac{d^2\pi_2}{dp_2^2} = -2\beta < 0 \quad (\text{B.1})$$

Since β is a positive parameter, the second derivative condition is clearly negative for both retailers.

Also, for the profit function of the 3PL company, the second-order derivation is:

$$\frac{d^2\pi_{3pl}}{dc_t^2} = -\frac{2\beta B_2}{4\beta^2 - \gamma^2} = -\frac{2\beta}{4\beta^2 - \gamma^2}(2\beta^2 - \gamma^2) < 0 \quad (\text{B.2})$$

Since $\beta > \gamma$, it is clear that Eq. (B.2) is a negative value.

Eq. (B.3) shows the Hessian matrix for the producer's profit function:

$$H_2 = \begin{bmatrix} -\eta & \frac{(2\beta + \gamma)\lambda(\beta\gamma + 2B_2)}{2(2\beta - \gamma)B_2} & \frac{\beta\lambda(-2\beta^2 + \beta\gamma + \gamma^2 + 4B_2)}{2(2\beta - \gamma)B_2} \\ \frac{(2\beta + \gamma)\lambda(\beta\gamma + 2B_2)}{2(2\beta - \gamma)B_2} & \frac{\beta\gamma^2(2\beta + \gamma) + (-4\beta^2 + 2\beta\gamma + 4\gamma^2)B_2}{(2\beta - \gamma)B_2} & \frac{\beta\gamma(-2\beta^2 + \beta\gamma + \gamma^2 + 4B_2)}{(2\beta - \gamma)B_2} \\ \frac{\beta\lambda(-2\beta^2 + \beta\gamma + \gamma^2 + 4B_2)}{2(2\beta - \gamma)B_2} & \frac{\beta\gamma(-2\beta^2 + \beta\gamma + \gamma^2 + 4B_2)}{(2\beta - \gamma)B_2} & \frac{\beta(\beta - \gamma)((\beta - \gamma)(2\beta + \gamma) - 4B_2)}{(2\beta - \gamma)B_2} \end{bmatrix} \quad (\text{B.3})$$

To have an optimal solution, the H_2 matrix must be negative-definite. Since $\eta > 0$, the condition $-\eta < 0$ is always satisfied. The following conditions must also be established for the H_2 matrix:

$$Z_1 = \begin{vmatrix} -\eta & \frac{(2\beta + \gamma)\lambda(\beta\gamma + 2B_2)}{2(2\beta - \gamma)B_2} \\ \frac{(2\beta + \gamma)\lambda(\beta\gamma + 2B_2)}{2(2\beta - \gamma)B_2} & \frac{\beta\gamma^2(2\beta + \gamma) + (-4\beta^2 + 2\beta\gamma + 4\gamma^2)B_2}{(2\beta - \gamma)B_2} \end{vmatrix} \quad (\text{B.4})$$

$$= -\frac{\left(\beta^2\gamma^2(2\beta + \gamma)^2\lambda^2 + 4B_2(\beta\gamma(2\beta + \gamma)((2\beta - \gamma)\eta + (2\beta + \gamma)\lambda^2)) + (2(-4\beta^3 + 4\beta^2\gamma + 3\beta\gamma^2 - 2\gamma^3)\eta + (2\beta + \gamma)^2\lambda^2)B_2 \right)}{4(-2\beta + \gamma)^2B_2^2} > 0$$

$$Z_2 = |H_2| = \frac{\left(\beta(\beta + \gamma)((\beta - \gamma)(2\beta + \gamma) - 4B_2)(\beta(\beta - 2\gamma)(2\beta + \gamma)\lambda^2) + (4(\beta - 2\gamma)(2\beta - \gamma)\eta - 2(4\beta + \gamma)\lambda^2)B_2 \right)}{2(-2\beta + \gamma)^2B_2^2} < 0 \quad (\text{B.5})$$

To have $Z_1 > 0$ and $Z_2 < 0$, the following condition must be established:

$$\eta > \frac{(14\beta^3 + 7\beta^2\gamma - 6\beta\gamma^2 - 2\gamma^3)\lambda^2}{4(\beta - 2\gamma)(2\beta - \gamma)(2\beta^2 - \gamma^2)} \quad (\text{B.6})$$

Appendix C. The concavity of profit functions in Problem III

The second-order derivative condition is:

$$\frac{d^2\pi_1}{dp_1^2} = \frac{d^2\pi_2}{dp_2^2} = -2\beta < 0 \quad (\text{C.1})$$

Since $\beta > 0$, $-2\beta < 0$ is a negative value.

In order to evaluate the optimality, the second-order derivative condition for the 3PL profit function is calculated as:

$$\frac{d^2\pi_{3pl}}{dc_t^2} = \frac{-4\beta^3 + 2\beta\gamma^2}{4\beta^2 - \gamma^2} = -2\beta \left(\frac{2\beta^2 - \gamma^2}{4\beta^2 - \gamma^2} \right) < 0 \quad (\text{C.2})$$

Since $\beta > \gamma$, $d^2\pi_{3pl}/dc_t^2 < 0$.

The Hessian matrix for the profit functions of the first and the second producers is obtained as follows.

$$H_3(\pi_{M_1}) = \begin{pmatrix} \frac{\partial^2 \pi_{M_1}}{\partial \theta^2} & \frac{\partial^2 \pi_{M_1}}{\partial \theta \partial w_1} & \frac{\partial^2 \pi_{M_1}}{\partial \theta \partial p_{d_1}} \\ \frac{\partial^2 \pi_{M_1}}{\partial w_1 \partial \theta} & \frac{\partial^2 \pi_{M_1}}{\partial w_1^2} & \frac{\partial^2 \pi_{M_1}}{\partial w_1 \partial p_{d_1}} \\ \frac{\partial^2 \pi_{M_1}}{\partial p_{d_1} \partial \theta} & \frac{\partial^2 \pi_{M_1}}{\partial p_{d_1} \partial w_1} & \frac{\partial^2 \pi_{M_1}}{\partial p_{d_1}^2} \end{pmatrix} \quad (C.3)$$

$$= \begin{pmatrix} -\eta & \frac{\beta(-\gamma\lambda_2 + 2\beta\lambda_1)}{8\beta^2 - 2\gamma^2} & \frac{(4\beta^2 + \beta\gamma - 2\gamma^2)(-\gamma\lambda_2 + 2\beta\lambda_1)}{2(2\beta - \gamma)(2\beta^2 - \gamma^2)} \\ \frac{\beta(-\gamma\lambda_2 + 2\beta\lambda_1)}{8\beta^2 - 2\gamma^2} & \frac{-2\beta^3 + \beta\gamma^2}{4\beta^2 - \gamma^2} & \frac{\beta\gamma}{2\beta - \gamma} \\ \frac{(4\beta^2 + \beta\gamma - 2\gamma^2)(-\gamma\lambda_2 + 2\beta\lambda_1)}{2(2\beta - \gamma)(2\beta^2 - \gamma^2)} & \frac{\beta\gamma}{2\beta - \gamma} & -4\gamma + \beta \left(-9 - \frac{8\beta}{-2\beta + \gamma} + \frac{2\beta(3\beta + 2\gamma)}{2\beta^2 - \gamma^2} \right) \end{pmatrix}$$

$$H_4(\pi_{M_2}) = \begin{pmatrix} \frac{\partial^2 \pi_{M_2}}{\partial w_2^2} & \frac{\partial^2 \pi_{M_2}}{\partial w_2 \partial p_{d_2}} \\ \frac{\partial^2 \pi_{M_2}}{\partial w_2 \partial p_{d_2}} & \frac{\partial^2 \pi_{M_2}}{\partial p_{d_2}^2} \end{pmatrix} \quad (C.4)$$

$$= \begin{pmatrix} \frac{-8\beta^5 + 9\beta^3\gamma^2 - 2\beta\gamma^4}{8\beta^4 - 6\beta^2\gamma^2 + \gamma^4} & \frac{\beta\gamma(4\beta^2 + \beta\gamma - 2\gamma^2)}{(2\beta - \gamma)(2\beta^2 - \gamma^2)} \\ \frac{\beta\gamma(4\beta^2 + \beta\gamma - 2\gamma^2)}{(2\beta - \gamma)(2\beta^2 - \gamma^2)} & -4\gamma + \beta \left(-9 - \frac{8\beta}{-2\beta + \gamma} + \frac{2\beta(3\beta + 2\gamma)}{2\beta^2 - \gamma^2} \right) \end{pmatrix}$$

where $H_3(\pi_{M_1})$ and $H_4(\pi_{M_2})$ are the Hessian matrix of the first and the second producers respectively. If the following conditions are satisfied for the parameters, $H_3(\pi_{M_1})$ and $H_4(\pi_{M_2})$ will be negative-definite:

$$-\eta < 0 \quad (C.5)$$

$$Z_3 = \frac{\beta(32\beta^4\eta + 4\gamma^4\eta - \beta\gamma^2\lambda_2^2 - 4\beta^3\lambda_1^2 + 4\beta^2\gamma(-6\gamma\eta + \lambda_1\lambda_2))}{4(-4\beta^2 + \gamma^2)^2} > 0 \quad (C.6)$$

$$Z_4 = -\frac{\begin{pmatrix} \beta(\beta + \gamma)(32\beta^6\eta + \gamma^5(-4\gamma\eta + \lambda_2^2) + 2\beta\gamma^4(-2\gamma\eta + \lambda_2(\lambda_2 - 2\lambda_1)) \\ + \beta^2\gamma^3(28\gamma\eta - 3\lambda_2^2 - 8\lambda_2\lambda_1 + 4\lambda_1^2) - 4\beta^5(8\gamma\eta + 5\lambda_1^2) \\ + \beta^3\gamma^2(24\gamma\eta - 5\lambda_2^2 + 12\lambda_2\lambda_1 + 8\lambda_1^2) - 4\beta^4\gamma(14\gamma\eta + \lambda_1(-5\lambda_2 + 3\lambda_1)) \end{pmatrix}}{(2\beta^2 - \gamma^2)(-4\beta^2 + \gamma^2)^2} < 0 \quad (C.7)$$

$$Z_5 = \frac{-8\beta^5 + 9\beta^3\gamma^2 - 2\beta\gamma^4}{8\beta^4 - 6\beta^2\gamma^2 + \gamma^4} < 0 \quad (C.8)$$

$$Z_6 = \frac{2\beta(8\beta^5 - 23\beta^3\gamma^2 - 12\beta^2\gamma^3 + 7\beta\gamma^4 + 4\gamma^5)}{8\beta^4 - 6\beta^2\gamma^2 + \gamma^4} > 0 \quad (C.9)$$

Since $\eta > 0$, Eq. (C.5) is already satisfied. To satisfy Eqs (C.6)–(C.9), the following conditions are necessary for the parameters:

$$\begin{cases} \eta > \frac{(5\beta^3 + 3\beta^2\gamma - 2\beta\gamma^2 - \gamma^3)(\gamma\lambda_2 - 2\beta\lambda_1)^2}{4(2\beta - \gamma)(2\beta + \gamma)(2\beta^2 - \gamma^2)(\beta^2 - \beta\gamma - \gamma^2)} \\ \beta > \frac{\gamma}{2} + \frac{1}{2}\sqrt{5}\sqrt{\gamma^2} \end{cases} \quad (C.10)$$

Appendix D. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cie.2021.107490>.

References

- Abbasi, S., Saboury, A., & Jabalameli, M. S. (2021). Reliable supply chain network design for 3PL providers using consolidation hubs under disruption risks considering product perishability: An application to a pharmaceutical distribution network. *Computers & Industrial Engineering*, 152, Article 107019.
- Amrouche, N., & Yan, R. (2013). Can a weak retailer benefit from manufacturer-dominant retailer alliance? *Journal of Retailing and Consumer Services*, 20, 34–42.

- Barari, S., Agarwal, G., Zhang, W. C., Mahanty, B., & Tiwari, M. (2012). A decision framework for the analysis of green supply chain contracts: An evolutionary game approach. *Expert Systems with Applications*, 39, 2965–2976.
- Cao, J., & Zhang, X. (2013). Coordination strategy of green supply chain under the free market mechanism. *Energy Procedia*, 36, 1130–1137.
- Chen, L., He, F., Zhang, Q., Jiang, W., & Wang, J. (2017). Two-stage efficiency evaluation of production and pollution control in Chinese iron and steel enterprises. *Journal of Cleaner Production*, 165, 611–620.
- Chen, Y. C., Fang, S.-C., & Wen, U.-P. (2013). Pricing policies for substitutable products in a supply chain with Internet and traditional channels. *European Journal of Operational Research*, 224, 542–551.
- Daryanto, Y., Wee, H. M., & Astanti, R. D. (2019). Three-echelon supply chain model considering carbon emission and item deterioration. *Transportation Research Part E: Logistics and Transportation Review*, 122, 368–383.
- Gao, J., Han, H., Hou, L., & Wang, H. (2016). Pricing and effort decisions in a closed-loop supply chain under different channel power structures. *Journal of Cleaner Production*, 112, 2043–2057.
- Ghosh, D., & Shah, J. (2012). A comparative analysis of greening policies across supply chain structures. *International Journal of Production Economics*, 135, 568–583.
- Giri, B., & Sarker, B. R. (2017). Improving performance by coordinating a supply chain with third party logistics outsourcing under production disruption. *Computers & Industrial Engineering*, 103, 168–177.
- Hafezalkotob, A. (2015). Competition of two green and regular supply chains under environmental protection and revenue seeking policies of government. *Computers & Industrial Engineering*, 82, 103–114.
- Hafezalkotob, A., & Mahmoudi, R. (2017). Selection of energy source and evolutionary stable strategies for power plants under financial intervention of government. *Journal of Industrial Engineering International*, 1–11.
- Hafezalkotob, A., Mahmoudi, R., Hajisami, E., & Wee, H. M. (2018). Wholesale-retail pricing strategies under market risk and uncertain demand in supply chain using evolutionary game theory. *Kybernetes*.
- Halat, K., & Hafezalkotob, A. (2019). Modeling carbon regulation policies in inventory decisions of a multi-stage green supply chain: A game theory approach. *Computers & Industrial Engineering*, 128, 807–830.
- Hua, G., Wang, S., & Cheng, T. E. (2010). Price and lead time decisions in dual-channel supply chains. *European Journal of Operational Research*, 205, 113–126.
- Huang, S., Fan, Z.-P., & Wang, X. (2019). The impact of transportation fee on the performance of capital-constrained supply chain under 3PL financing service. *Computers & Industrial Engineering*, 130, 358–369.
- Huang, S., Yang, C., & Liu, H. (2013). Pricing and production decisions in a dual-channel supply chain when production costs are disrupted. *Economic Modelling*, 30, 521–538.
- Huang, Y., Wang, K., Zhang, T., & Pang, C. (2016). Green supply chain coordination with greenhouse gases emissions management: A game-theoretic approach. *Journal of Cleaner Production*, 112, 2004–2014.
- Huang, Y., & Wang, Z. (2017). Closed-loop supply chain models with product take-back and hybrid remanufacturing under technology licensing. *Journal of cleaner production*, 142, 3917–3927.
- Jamali, M.-B., & Rasti-Barzoki, M. (2019). A game theoretic approach to investigate the effects of third-party logistics in a sustainable supply chain by reducing delivery time and carbon emissions. *Journal of Cleaner Production*, 235, 636–652.
- Javadi, T., Alizadeh-Basban, N., Asian, S., & Hafezalkotob, A. (2019). Pricing policies in a dual-channel supply chain considering flexible return and energy-saving regulations. *Computers & Industrial Engineering*, 135, 655–674.
- Jiang, L., Wang, Y., & Yan, X. (2014). Decision and coordination in a competing retail channel involving a third-party logistics provider. *Computers & Industrial Engineering*, 76, 109–121.
- Karimabadi, K., Arshadi-khamseh, A., & Naderi, B. (2020). Optimal pricing and remanufacturing decisions for a fuzzy dual-channel supply chain. *International Journal of Systems Science: Operations & Logistics*, 7, 248–261.
- Kayvanfar, V., Husseini, S. M., Karimi, B., & Sajadieh, M. S. (2017). Bi-objective intelligent water drops algorithm to a practical multi-echelon supply chain optimization problem. *Journal of Manufacturing Systems*, 44, 93–114.
- Kayvanfar, V., Husseini, S. M., NengSheng, Z., Karimi, B., & Sajadieh, M. S. (2019). A practical supply-demand hub in industrial clusters: A new perspective. *Management Research Review*.
- Kayvanfar, V., Moattar Husseini, S., Karimi, B., & Sajadieh, M. S. (2018). Supply-demand hub in industrial clusters: A stochastic approach. *Engineering Optimization*, 50, 1561–1577.
- Kayvanfar, V., Sajadieh, M. S., Husseini, S. M., & Karimi, B. (2018). Analysis of a multi-echelon supply chain problem using revised multi-choice goal programming approach. *Kybernetes*.
- Li, B., Hou, P.-W., Chen, P., & Li, Q.-H. (2016). Pricing strategy and coordination in a dual channel supply chain with a risk-averse retailer. *International Journal of Production Economics*, 178, 154–168.
- Li, B., Zhu, M., Jiang, Y., & Li, Z. (2016). Pricing policies of a competitive dual-channel green supply chain. *Journal of Cleaner Production*, 112, 2029–2042.
- Lieb, R. C. (1992). The use of third-party logistics services by large American. *Journal of Business Logistics*, 13, 29.
- Liu, H., Zhang, Y., Zhu, Q., & Chu, J. (2017). Environmental efficiency of land transportation in China: A parallel slack-based measure for regional and temporal analysis. *Journal of Cleaner Production*, 142, 867–876.
- Liu, Y., Li, J., Ren, W., & Forrest, J. Y.-L. (2020). Differentiated products pricing with consumer network acceptance in a dual-channel supply chain. *Electronic Commerce Research and Applications*, 39, Article 100915.
- Mahmoudi, R., Emrouznejad, A., Shetab-Boushehri, S.-N., & Hejazi, S. R. (2020). The origins, development and future directions of data envelopment analysis approach in transportation systems. *Socio-Economic Planning Sciences*, 69, Article 100672.
- Mahmoudi, R., Hafezalkotob, A., & Makui, A. (2014). Source selection problem of competitive power plants under government intervention: A game theory approach. *Journal of Industrial Engineering International*, 10, 1–15.
- Mahmoudi, R., & Rasti-Barzoki, M. (2018). Sustainable supply chains under government intervention with a real-world case study: An evolutionary game theoretic approach. *Computers & Industrial Engineering*, 116, 130–143.
- Mahmoudi, R., Shetab-Boushehri, S.-N., Hejazi, S. R., & Emrouznejad, A. (2019). Determining the relative importance of sustainability evaluation criteria of urban transportation network. *Sustainable Cities and Society*, 47, Article 101493.
- Mahmoudi, R., Shetab-Boushehri, S.-N., Hejazi, S. R., Emrouznejad, A., & Rajabi, P. (2019). A hybrid egalitarian bargaining game-DEA and sustainable network design approach for evaluating, selecting and scheduling urban road construction projects. *Transportation Research Part E: Logistics and Transportation Review*, 130, 161–183.
- Maiti, T., & Giri, B. (2015). A closed loop supply chain under retail price and product quality dependent demand. *Journal of Manufacturing Systems*, 37, 624–637.
- Qi, Q., Wang, J., & Bai, Q. (2017). Pricing decision of a two-echelon supply chain with one supplier and two retailers under a carbon cap regulation. *Journal of Cleaner Production*, 151, 286–302.
- Rezaee, A., Dehghanian, F., Fahimnia, B., & Beamon, B. (2017). Green supply chain network design with stochastic demand and carbon price. *Annals of Operations Research*, 250, 463–485.
- Rodrigues, A. C., Martins, R. S., Wanke, P. F., & Siegler, J. (2018). Efficiency of specialized 3PL providers in an emerging economy. *International Journal of Production Economics*, 205, 163–178.
- Sheu, J.-B., & Chen, Y. J. (2012). Impact of government financial intervention on competition among green supply chains. *International Journal of Production Economics*, 138, 201–213.
- Srivastava, S. K. (2007). Green supply-chain management: A state-of-the-art literature review. *International journal of management reviews*, 9, 53–80.
- Swami, S., & Shah, J. (2013). Channel coordination in green supply chain management. *Journal of the operational research society*, 64, 336–351.
- Taleizadeh, A. A., Haghighi, F., & Niaki, S. T. A. (2019). Modeling and solving a sustainable closed loop supply chain problem with pricing decisions and discounts on returned products. *Journal of cleaner production*, 207, 163–181.
- Wang, F., Yang, X., Zhuo, X., & Xiong, M. (2019). Joint logistics and financial services by a 3PL firm: Effects of risk preference and demand volatility. *Transportation Research Part E: Logistics and Transportation Review*, 130, 312–328.
- Wang, L., Song, H., & Wang, Y. (2017). Pricing and service decisions of complementary products in a dual-channel supply chain. *Computers & industrial engineering*, 105, 223–233.
- Xu, S., Liu, Y., & Chen, M. (2017). Optimisation of partial collaborative transportation scheduling in supply chain management with 3PL using ACO. *Expert Systems with Applications*, 71, 173–191.
- Yan, R., Guo, P., Wang, J., & Amrouche, N. (2011). Product distribution and coordination strategies in a multi-channel context. *Journal of Retailing and Consumer Services*, 18, 19–26.
- Yan, R., & Pei, Z. (2009). Retail services and firm profit in a dual-channel market. *Journal of Retailing and Consumer Services*, 16, 306–314.
- Yao, Z., Leung, S. C., & Lai, K. K. (2008). Manufacturer's revenue-sharing contract and retail competition. *European Journal of Operational Research*, 186, 637–651.
- Zhang, C.-T., Wang, H.-X., & Ren, M.-L. (2014). Research on pricing and coordination strategy of green supply chain under hybrid production mode. *Computers & Industrial Engineering*, 72, 24–31.
- Zhao, J., Wei, J., & Li, Y. (2018). Pricing decisions of complementary products in a two-level fuzzy supply chain. *International Journal of Production Research*, 56, 1882–1903.
- Zhu, Q., Sarkis, J., & Lai, K.-H. (2008). Green supply chain management implications for “closing the loop”. *Transportation Research Part E: Logistics and Transportation Review*, 44, 1–18.