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RESEARCH PAPER

# A Game Theoretical Approach to Competition Between Members of a Green Supply Chain with Hybrid Products

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## Abstract

With progressing technologies, green products are in competition with non-green products. In the real world, there exist many firms that produce green and non-green products. In this study, a green supply chain (GSC) with a supplier and a manufacturer is considered. The supply chain (SC) produces green and non-green products. Market demands for both non-green and green products are available. These products might be replaced with each other. If the demand isn't satisfied by green products, a hybrid production mode involving green and non-green products is chosen by the manufacturer. The government is considered as the leader of the game and fixes special tariffs(tax and subsid) for all products to control the market demand. A game theoretical model is formulated in four scenarios by considering the collaboration of members in the SC. The ideal prices of raw materials, selling prices, and demand for green and non-green products are calculated. A numerical example that consists of sensitivity analysis of some main parameters is presented to compare the outcomes of various scenarios. The results indicate that collaboration between supplier and manufacturer has a significant impact on the profit of GSC. Besides, Various consumer's priorities are covered in hybrid production mode. The results show that by choosing hybrid production mode, the profit of SC decreases and hybrid production mode has no positive role on profit of SC and membership. Sensitive analysis shows that increasing tariffs by the government causes an increase in summation profit function of GSC and profit function of a member of GSC. Moreover, the demand for non-green products increases.

**Keywords:**
Competition;
Cooperation;
Game Theory;
Green Supply Chain;
Hybrid

## Introduction

Green products (GPs) and non-green products (NGPs) differ in conditions of environmental functionality. GPs refer to environmental protecting, nontoxic, and recycled materials. For example, electrical cars are GPs. GPs' costs are normally higher than NGPs. For the past 20 years, people have been highly concerned about environmental effects. In the year 2021, 18 out of 20 people worldwide breathe polluted air and 500 billion to 1.5 trillion plastic bags end up in landfills each year. These examples show great care of consumers toward GPs.

The research from 2018 shows that seventy five percent of the buyers among seventy countries are wicking to pay more for green GPs and the demand for GPs has doubled in

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comparison with the last five years. People are more sensitive to the environment. In other words, increasing temperature of the world has been considered as an international problem. This concern is greatly affecting buyers' pur tax try to reduce carbon dioxide. Carbon taxes have been implemented in 25 countries.

The environmental assessment tools can help customers to assess the environmental effects of electronic devices. The products like an engine of automotive are rated as gold, silver or bronze depending upon the environmental performance. A hybrid automotive uses various modes of power like electric generators and internal combustion engines.

Generally, governments implement policies such as taxes and subsidies to NGPs to decrease environmental pollution. Environmental policy is any policy that is implemented by a government to reduce the effects of human activities on the environment. Environmental policies are really necessary because environmental pollution is not noticed in the decisions of many organizations. In other words, environmental policy is the commitment of governments to implement mechanisms to decrease environmental concerns. As a case in point, Japan's government implements market-based instruments in the dish disposable market to decrease the selling price for green products and to encourage customers to buy green products.

Some advantages of environmental policies of government are as follows:

-Making the environment sustainable for future generations

-Saving energy and natural resources

-Reducing pollution and greenhouse gas emissions

In this study, the role of government in increasing the demand of GPs and NGPs is investigated.

Governments have many tools to manage environmental pollutions such as water pollution, global warming, and air pollution. The policies of governments directly affect the environment. Besides, there are some regulations like a carbon tax to obligate governments to pay attention to the environmental problems. A carbon tax is a tax relevant to carbon emissions. Until 2030, all countries in the world are obligated to pay a carbon tax.

In this study, the government is considered as the leader because it fixes tariffs for GPs and NGPs in order to control the demand. The government has a responsibility for decreasing environmental pollutions. Tariffs are considered as a fixed parameter. By fixing tariffs, the suppliers and the manufacturers are motivated to produce GPs. Producing GPs provides higher environmental protection and more competitive advantages. The aim of this paper is to study ordering decisions on pricing under a hybrid GSC.

In this study, we focus on a bi-level GSC under green and hybrid production modes with government intervention. The main research questions of this study are as follows:

1. What are the prices of raw materials and the ideal selling prices?
2. What is the best strategy for the government and what are the suitable strategies of suppliers and manufacturers in different scenarios?
3. Is collaboration beneficial for SC and the members?
4. How are the interactions between the members of GSC under different production modes?

The organization of this study is as follows: Section 2 presents a literature review. Section 3 presents the notations and assumptions. Section 4 presents the model formulation and sensitivity analysis. Section 5 provides some numerical examples and managerial insights and we end with conclusions.

## Literature review

This paper is relevant to pricing and hybrid production concept in GSCs under government intervention. These topics are studied in the following subsections.

## Pricing and hybrid production concept in GSCs

GSCM consists of customization of the flow of information and materials and collaboration among the supplier and the members of SC. The pricing decision is highly vital since it instantly affects the profits of members in SC and market demand. Also, green products are those products that supply social benefits and environmental protection. LED light, energy-saving TV, green power outlet are some examples of green products. Taleizadeh et al. [24] developed a closed-loop supply chain including one manufacturer, one retailer and a third party, in which the manufacturer produces a product under appropriate quality and sells it through a retailer in the market. Hafezalkotob [7] worked on a collaboration between members of GSC. GSC produces multi-products. Taleizadeh et al. [23] investigated a model based on market noise effects and disarray. Game theory was used for solving this model, in which the retailers are followers and the manufacturer is the leader.

Taleizadeh et al. [29] investigated the pricing strategies of a manufacturer and a retailer on an SC with a recycling member. Daryan et al. [19] developed an economic production quantity model in a three-layer supply chain with two different structures. This chain composed of a supplier, a manufacturer, and multiple retailers. Zhao et al. [26] studied GCS with hybrid products. They investigated the competition between members of GCS. They did not study the role of government in their model. Therefore, their model was not realistic.

Rasti et al. [21] studied cooperation in SC with hybrid production mode. They ignored the role of government. Khalafi et al. [14] worked on a case study that included SC with the multi product. Jolai et al. [12] examined a reverse logistics system, including one manufacturer along with a collector who collects used products based on the consumers' willingness to return such products. Abdolazimi et al. [1] studied a bi-objective mixed-integer linear programming model to minimize the overall cost and maximize the use of eco-friendly materials and clean technology. Hafezalkotob [17] presented a model with GSC including a manufacturer and a supplier. This GSC produces only green products. The effects of variable services on the selling price and profit of GSC are studied. The cost of advertising and maintenance is ignored. Thus, the proposed model was not realistic. Hadi et al. [6] considered green and regular SCs. In their research, each SC consists of a manufacture and a retailer. The GSC consists of a recycler. The government acts as the leader and fixes tariffs for green and non-green products to control the market and environmental pollution. The tariffs were considered as a fixed parameter. The pricing mechanism was a controlling tool for members of SC.

## The government intervention on green supply chains

Governments are responsible for decreasing environmental pollutions. SCs show reaction to government tariffs so that they increase their activities in the environment industry. Hafezalkotob and Hadi [8] formulated the competition of a closed loop SC and an ordinary SC, using game theory. The effects of the government's strategies are studied. Hafezalkotob [7] proposed a new model for competition among GCS and regular SC, under government policies. The government had different policies such as environment protection, and revenue seeking. The costs of maintenance, advertising, and service are ignored. Therefore, the proposed model was not realistic. Hafezalkotob [7] investigated price and energy-saving models in two GSCs with government intervention and the ideal tariffs and retail prices of the SCs are found.

Zerang and Razmi [29] modeled closed loop SC with a manufacturer, a retailer, and a third party. The ideal decisions and ideal variables under various scenarios in centralized and decentralized scenarios are investigated. The result showed that the governments have an important role in increasing or decreasing environmental pollution by tariffs. Sinayi and Rasti [21] studied an SC including a retailer and a manufacturer. Green products are produced in the

SC and government acts as the leader of the game. The completion between members of GSC is investigated. The result illustrated that the governments have a critical role in increasing social welfare and selling price. The proposed model was not realistic because the completion among GSC was ignored.

Yazdanpanah et al. [28] studied the competition among green manufacturers, green suppliers, ordinary manufacturers, ordinary suppliers, and government. Green supplier and manufacturer were members of an SC and ordinary supplier and manufacturer were members of other SCs. Moreover, the members of SC should be controlled to increase the profit and decrease environmental pollutions. Also, Javadi et al. [11], Gharehbagh et al. [13], and Khosroshahi et al. [15] studied the role of government in GSCs. Hadi et al. [5] considered market demands so that green and non-green products can be substituted with each other and a dual channel with government intervention was studied. Chang et al. [27] et al investigated the role of government in GSC with multi products. Hafezalkotob [17] presented a model with SC including a manufacturer, a supplier, and a recycler. This SC produces only one product. He investigated the effects of variable advertising on the profit of SC. Moreover, he studied the role of government in SC. Table 1 presents the characteristics of the mentioned papers on the competition of SCs.

**Table 1.** Characteristics of the published papers on competition of SCs.

| **Reference** | **Competition** | | | | | | | | | | **Approach** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Green Supply Chain | Hybrid production | Competition among SCs or between members of SC | Government intervention | cooperation | **product** Multi | **product** one | **Game Theory** GEA | **Game Theory** Nash | **Game Theory** Stackelberg | Decision making structure | Case study |
| Hafezalkotob [7] | * | | | * | * | * | | | | * | Bilevel | |
| Hadi et al. [8] | * | * | * | * | | | | | * | * | Bilevel | |
| Hafezalkotob [9] | * | | | | * | * | | | | * | Multilevel | * |
| Sinayi and Rasti [21] | * | | | * | * | | * | | | * | Bilevel | |
| Esmaili and Zandi [4] | * | | | * | | | * | | | * | Bilevel | |
| Hafezalkotob [10] | * | | | * | | * | | | | * | Bilevel | |
| Mahmoudi et al. [16] | * | * | | * | | * | | | | * | Bilevel | |
| Talebizadeh and Sadeghi [25] | | * | | | | | * | | * | * | Bilevel | |
| Zhao et al. [26] | * | * | | | | | * | | | * | Bilevel | |
| Javadi et al. [11] | * | | | * | | | * | | | * | Multi-level | |
| Gharehbagh et al. [13] | * | | | * | | | * | | | * | Bilevel | |
| Khosroshahi et al. [15] | * | | | * | * | | * | | | * | Bilevel | |
| Yazdanpanah et al. [28] | * | * | | * | | * | | | | * | Bilevel | |
| Rasti et al. [19] | | * | | | * | | * | | | * | Bilevel | |
| Hadi et al. [5] | * | * | | * | | * | | | | * | Bilevel | * |
| Khalafi et al. [14] | | * | | | | * | | | | | Multilevel | * |
| Jolai et al. [12] | * | | * | | | | * | | | | Multilevel | |
| Hadi et al. [6] | * | | * | * | * | * | | | | * | Bilevel | |
| Hafezalkotob et al. [11] | * | | * | * | | | * | | | * | Bilevel | |
| Hafezalkotob et al. [17] | * | | * | | * | | * | | | * | Bilevel | |
| Chang et al. [27] | * | | | * | | * | | | | * | Bilevel | |
| This paper | * | * | * | * | * | * | | | | * | Bilevel | |

**Research gap**

The effects of government intervention on GSC (specially government's financial tool) have been studied on a few papers of game theory. The government used inspiration and punishments to use negative and positive impacts, respectively [2,3,20]. Murphy [18] studied the various policies of the government. Hafzalkotob [5] studied the coordination and pricing in green and ordinary SC. In most of the previous studies, the demand function has not been defined nonlinearly. Also, in most of previous articles, the role of the government in increasing or decreasing the demand of GPs and NGPs was ignored.
As far as the authors know, no research has been done on the pricing of hybrid GSC under government intervention. In this paper, for the first time, we develop an integrated model that simultaneously considers hybrid production mode in one GSC, nonlinear demand function and government interaction in GSC. In fact, we consider the competition of hybrid GSC with nonlinear demand of the market. By investigating the articles of completion in GSCs, the following critiques can be provided: (i) We investigate various decision-making structures. By providing fixed tariffs, players try to achieve equilibrium. (ii) Manufacturers and suppliers in GSC might have various options for their productions. (iii) A competition in different scenarios in centralized and decentralized SC is modeled by the Stackelberg approach. This study investigates the model of the pricing of GSC. We concentrate on market demand of green and non-green products which can be replaced with each other. In the real world, there exist many firms that produce GPs and NGPs. In this article, we consider hybrid SCs that produce GPs and NGPs.
We study the model in 4 different scenarios (centralized and decentralized games) for decision-making structures of GSC and various modes of products (green and non-green products).

## Parameters and assumptions

The GSC includes a manufacturer and a supplier. The manufacturer can produce green and non-green productions. The supplier provides non-green and green raw materials. The government is considered as the leader and the tariffs are considered as fixed parameters.
The complying notations are as follows:

**Parameters:**

| | |
|---|---|
| $C_R$ | The manufacture's unit production cost of GPs; |
| $C_S$ | The supplier's fixed cost of sales; |
| $C_r$ | The manufacturer's unit production cost of NGPs; |
| V | The buyer's value preposition for GPs; |
| $\pi_S$ | The profit of the supplier; |
| $\pi_M$ | The profit of the manufacturer; |
| $w_n$ | The prices of raw material for NGPs; |
| $w_g$ | The prices of raw material for GPs; |
| $p_n$ | The prices of NGPs supplied by the manufacturer; |
| $p_g$ | The prices of GPs supplied by the manufacturer; |
| $t_g$ | The tariff of NGPs supplied by the manufacturer; |
| $t_n$ | The tariff of GPs supplied by the manufacturer; |

**Assumptions:**

**Assumption 1.** We assume that
$W_g > W_n > C_s$ ; $P_g > P_n$ , $C_R > C_r$. The GPs and NGPs have the same functionality.

**Assumption 2.** The GPs and the NGPs differ in price, tax, and value preposition for buyers. We assume V to uniform distribution of [0, A].

$W_g + C_R < A$ . We consider $\lambda_v$ as the buyer valuation of non–green products. $U_g$ and $U_n$ are as follows:

$$U_g = V - (P_g + t_g) \quad (1)$$

$$U_n = \lambda V - (P_n + t_n) \qquad (0 \prec \lambda \prec 1) \quad (2)$$

When $U_g > U_n$ , the buyers buy GPs.
When $U_g < U_n$ , the buyers buy NGPs.

**Assumption 3.** The solution concept is the Stackelberg model. The supplier as the leader of the game concurrently specifies the prices of non-green and green raw materials.

**Assumption 4.** The members of GSC have rational behavior.

## The model formulation

The GSC includes two members, a supplier and a manufacturer. The manufacturer selects various production cases according to the demand market for GPs and NGPs. The supplier provides raw materials of GPs for the manufacturer. When customers are not interested in buying GPs, manufacturers choose hybrid production cases. Hybrid production case involves NGPs and GPs. The government set tariffs for GPs and NGPs. The tariffs are fixed parameters. Fig. 1 shows a two-stage GSC framework.

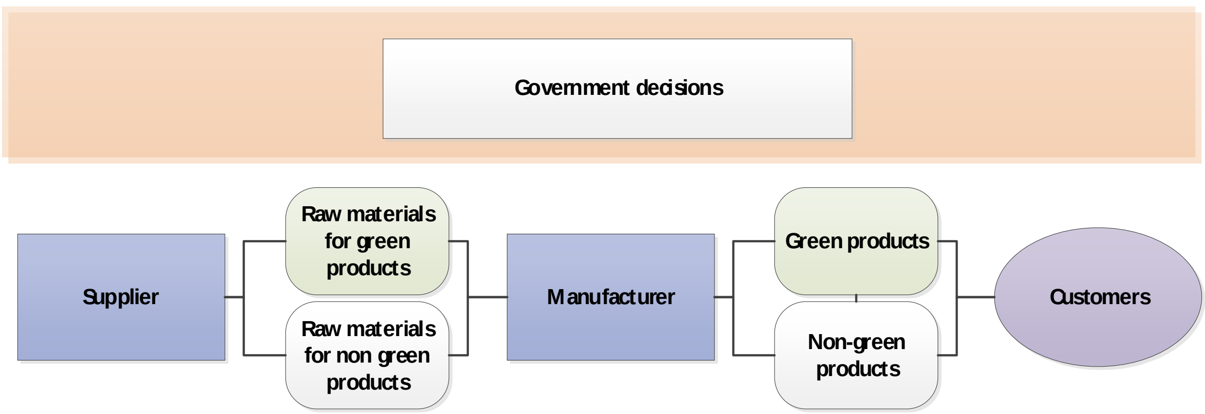


**Fig. 1.** The typical framework between SC's members

Fig. 2 illustrates 4 scenarios for modelling the game based on the collaboration and modes of products.

We study the model under centralized and decentralized structures and modes of the product by a backward induction technique.

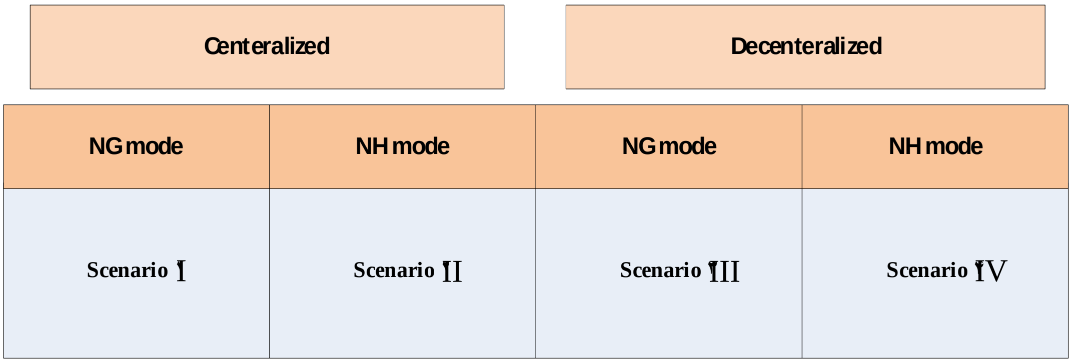


**Fig. 2**. Game structures of SC

**Pricing strategy in decentralized game with NG mode**

The supplier provides green raw materials and the manufacturer produces GPs and buys green raw materials. It is assumed that the GSC produce only GPs.

If $\lambda p_g + t_g < p_n + t_n < p_g + t_g$ then $\lambda_V - (p_g + t_g) < \lambda_V - (\lambda p_g + \lambda t_g) < V - (p_g + t_g)$,

, i.e. < $U_g$; that is, there is just buyer demand for GPs in the market.

In this state, green production mode is chosen by the manufacturer.

If $Ug = V - (p_g + t_g)$ then $V > p_g + t_g$

If $V \sim U\,[0, A]$, the market demand for GPs is as follows:

$$Q_g = l.\int_{P_g+t_g}^{A} \frac{1}{A} dv = \frac{A-(P_g+t_g)}{A} \tag{3}$$

The demand for NGPs is equal to zero ($Q_n = 0$)

The decision model for the supplier and the manufacturer in the case of producing only green products is:

$$\max_{W_g} \pi_s = (W_g - C_s)\frac{A-(P_g+t_g)}{A} \tag{4}$$

$$s.t.\begin{cases} \max\limits_{P_g} \pi_m = (P_g - W_g - C_r)\dfrac{A-(P_g+t_g)}{A} \\ 0 \prec W_g \prec P_g \prec V \end{cases} \tag{5}$$

The solution of problem is characterized by the Stackelberg model as follows:

**Step 1**. Supplier simultancelly defines their prices of raw material for GPs. The ideal value of $W_g^{NG}$ is found.

**Step 2**. The manufacturer determines prices of products. The manufacturer specifies the ideal value of $\widetilde{P}_g^{NG}$ as the follower.

By backward approach, we solve the problem.

The profit function of the manufacturer is concave. Therefore, we calculate the ideal price for GPs.

$\pi_M$ is a concave function on $P_g$.

$\frac{\partial^2 \pi_M}{\partial P_g^2}$=-2/A<0

The ideal $P_g$ that maximizes $\pi_M$ is obtained as follows:

$\frac{\partial \pi_M}{\partial p_g}$ =0,

$$P_g^{NG} = (A + W_g + C_R - t_g)/2 \tag{6}$$

The profit function of the supplier is concave. The prices of raw material for GPs can be found by substituting the price for GPs supplied by the manufacturer in Eq. 4.

The profit function of the supplier is concave and the ideal raw material price for GPs is:

$\pi_s$ is concave function on $W_g$ .

$$\max_{W_g} \pi_s = (W_g - C_s).\frac{A-(P_g+t_g)}{A}$$

$$\frac{\partial^2 \pi_s}{\partial w_g^2} =<0,$$

The ideal $W_g$ that maximizes the $\pi_s$ is obtained as follows:

$$\frac{\partial \pi_S}{\partial w_g} = 0,$$

$$W_g^{NG} = \frac{C_s - C_R}{2} \tag{7}$$

By substituting $W_g^{NG}$ in the price of GPs, the ideal price for GPs is as follows:

$$P_g^{NG} = (2A + C_R + C_s - 2t_g)/4 \tag{8}$$

**Pricing strategy in decentralized game with NH mode**

If the demand is not satisfied by GPs, a hybrid production mode involving GPs and NGPs is chosen by the manufacturer. In this scenario, it is assumed that the market demand is not covered by GPs. Therefore, manufacturers choose NH mode including producing N GPs and GPs.

If $p_n + t_n < \lambda\ (p_g + t_g)$, there are two productions' utilities as follows:

1- $Ug > Un$;

2- 2- $Ug \le Un$.

In NH mode, the manufacturer produces NGPs and GPs at the same time.

If $Ug > Un$, then $v > \frac{P_g+t_g-P_n-t_n}{1-\lambda}$ .

*For* $V \sim U[0, A]$ , market demand for GPs is as follows:

$$Q_g = 1.\int^A \frac{P_g + t_g - P_n - t_n}{1-\lambda} \frac{1}{A} dv = 1 - \frac{P_g + t_g - P_n - t_n}{A(1-\lambda)} \tag{9}$$

If $U_g \le U_n$ and $U_n > 0$, i.e

$\frac{P_n+t_n}{\lambda} < V \le \frac{P_g+t_g-(P_n+t_n)}{(1-\lambda)}$ For $V \sim U[0, A]$, there is market demand for NGPs.

$$Q_n = 1.\int_{\frac{P_n+t_n}{\lambda}}^{\frac{P_g+t_g-(P_n+t_n)}{1-\lambda}} \frac{1}{A} dv = \frac{\lambda(P_g+t_g)-(P_n+t_n)}{(1-\lambda)A\lambda} \quad (10)$$

The decision model for the supplier and the manufacturer in the case of producing GPs and GPs (NH mode) is as follows:

$$\max_{W_g,W_n} \pi_s = (W_g - C_s).(1-\frac{P_g+t_g-P_n-t_n}{(1-\lambda)A}) + (W_n - C_s).(1-\frac{\lambda(P_g+t_g)-(P_n+t_n)}{(1-\lambda)A\lambda}) \quad (11)$$

$$s.t. \begin{cases} \max_{P_g,P_n} \pi_m = (P_g - W_g - C_r).(1-\frac{P_g+t_g-P_n-t_n}{(1-\lambda)A}) + (P_n - W_n - C_r).(\frac{\lambda(P_g+t_g)-(P_n+t_n)}{(1-\lambda)A\lambda}) \\ 0 \prec P_n \prec \lambda P_g \end{cases} \quad (12)$$

The solution of problem is characterized by the Stackelberg model as follows:
**Step 1-** Supplier simultanslly defines their prices of raw material for green and non-green products. The ideal value of $W_g^{NH}$ and $W_n^{NH}$ are found.
**Step 2-** Manufacturer defines prices of GPs and NGPs. The manufacture specifies the ideal value of $\widetilde{P}_g^{N}$ and $\widetilde{P}_n^{N}$ as the follower.

We can solve the problem by backward approach. $\pi_M$ is a concave function on $\widetilde{P}_g^{NH}$ and $\widetilde{P}_n^{NH}$.

$$\frac{\partial^2 \pi_M}{\partial P_g^2} = <0$$
$$\frac{\partial^2 \pi_M}{\partial P_n^2} = <0$$

The Hessian matrix of objective function of the manufacturer is a concave function on $(\widetilde{P}_g^{NH}, \widetilde{P}_n^{NH})$ , if Hessian matrix $H_i$ is negatively defined.

The unique $\widetilde{P}_g^{NH}$ and $\widetilde{P}_n^{NH}$ that maximize the profit functions of the manufacturer are obtained as follows:

$$\frac{\partial \pi_M}{\partial \widetilde{P}_n^{NH}} = 0, \frac{\partial \pi_M}{\partial \widetilde{P}_n^{NH}} = 0,$$

The ideal price response function of the manufacturer is derived from Eq. 12 as follows:

$$\widetilde{P}_g^{NH} = e_1 W_n + y_1 W_g + h_1 t_g + k_1 t_n + c_1 \quad (13)$$

$$\widetilde{P}_n^{NH} = e_2 W_n + y_2 W_g + h_2 t_g + k_2 t_n + c_2 \quad (14)$$

By substituting the ideal value of $\widetilde{P}_g^{NH}$ and $\widetilde{P}_n^{NH}$ in the objective function of the supplier, we specify the ideal price of raw material for GPs and NGPs and price of green and non-green products. We can characterize the prices of raw materials of green and non-green products because the profit function of the supplier is concave.

If the profit function of the supplier is concave, the ideal raw material price is as follows:

$$W_g^{NH} = h_3 t_g + k_3 t_n + c_3 \quad (15)$$

$$W_n^{NH} = h_4 t_g + k_4 t_n + c_4 \tag{16}$$

**Pricing strategy in centralized game with NG mode**

The manufacturer produces GPs and buys green raw materials. The supplier and the manufacturer conduct joint decision–making in the principle of increasing SC benefits if they choose to coordinate. In this scenario, it is assumed that the GSC produces only GPs.

$$\max_{P_g} \pi = (P_g - P_R - C_s)\frac{A - P_g - t_g}{A} \tag{17}$$

The solution of problem is described by the Stackelberg model. $\pi_S$ is a concave function on $W_g^{NH}$ and $W_n^{NH}$.

$\frac{\partial^2 \pi_S}{\partial W_g^2} = <0$

$\frac{\partial^2 \pi_S}{\partial W_n^2} = <0$

The Hessian matrix of the profit function of the supplier is a concave function on $(W_g^{NH}, W_n^{NH})$ ,if Hessian matrix $H_i$ is negatively defined.

The unique $W_g^{NH}$ and $W_n^{NH}$ that maximize the objective functions supplier are obtained as follows:

$\frac{\partial \pi_S}{\partial w_n^{NH}}$ =0, $\frac{\partial \pi_S}{\partial w_n^{NH}}$=0,

The ideal price for GPs and NGPs in centralized game are as follows:

$$P_g = (3A - 3t_g + C_R + C_s)/2 \tag{18}$$

**Pricing strategy in centralized game with NH mode**

If the demand is not satisfied by green products, a hybrid production mode involving GPs and NGPs is chosen by the manufacturer. In this scenario, it is assumed that the market demand is not covered by GPs and SC chooses producing GPs and NGPs. In this case, SC provides NGPs and GPs. If the supplier and the manufacturer collaborate under the NH mode, the model is as follows:

$$\max_{P_g, P_n} \pi = (P_g - C_R - C_s).(1 - \frac{P_g + t_g - (P_n + t_n)}{(1-\lambda)A}) + (P_n - C_r - C_s).(\frac{\lambda(P_g + t_g) - (P_n + t_n)}{(1-\lambda)A\lambda}) \tag{19}$$

We can solve the problem by the Stackelberg model and using backward approach. The profit function of SC is a concave on $\widetilde{P}_n^N$ $and$ $\widetilde{P}_g^N$.

$\frac{\partial^2 \pi_s}{\partial P_g^2}$ =<0

$\frac{\partial^2 \pi_s}{\partial p_n^2} = <0$

The Hessian matrix of the objective function of GSC is a concave function on $(\widetilde{P}\,_n^N, \widetilde{P}\,_g^N)$ ,if Hessian matrix $H_i$ is negatively defined.

The unique $\widetilde{P}\,_n^N$ *and* $\widetilde{P}\,_g^N$ that maximize the profit function are obtained as follows:

$$\frac{\partial \pi}{\partial \widetilde{P}\,_n^N} = 0,\ \frac{\partial \pi}{\partial \widetilde{P}\,_g^N} = 0,$$

The ideal price response function of the manufacturer is found as follows:

$$P_g^N = h_5 t_g + k_5 t_n + c_5 \tag{20}$$

$$P_n^N = h_6 t_g + k_6 t_n + c_6 \tag{21}$$

**Corollary 1:** In pricing strategy in NG mode, from Eqs. 1 to 8 the following results are found:

- Considering $\frac{\partial P_g^{NG}}{\partial t_g} = -0.5$, variable $P_g^{NG}$ decreases by increasing $t_g$.
- Regarding $\frac{\partial W_g^{NG}}{\partial t_g} = 0$,variable $W_g^{NG}$ is constant by changing $t_g$.

**Corollary 2:** In pricing strategy in centralized game under NH mode, from Eqs. 17 and 18 the following results are found:

- Regarding $\frac{\partial P_g}{\partial t_g} = 0$,variable $P_g$ is constant by changing $t_g$.
- Considering $\frac{\partial P_g}{\partial t_n} = -0.5$, variable $P_g$ decreases by increasing $t_n$.

## Numerical example

### Discussing the scenarios

The presented model can be applied to the real world problems. As a case, a Chinses Motorcycle Company produced non-green and green products with similar features. The green and non-green motorcycles prices are completely different. The chiness government supports green products by subsidies and imposes various tariffs for non-green products.

In this subsection, a real numerical in China is shown to illustrate the price of green and non-green products in a GSC. It is aimed that 20% of automotive will be interested in electric cars by 2025. By 2029, the target is for 30% of new automotive to have electric power. The government fixes subsidies and tariffs for green and non-green automotive to control environmental pollution and social welfare. In this section, some numerical examples are presented to illustrate aspects of the models. It is considered that $\varphi_i = 0.5$(i=1,2),$a_i = 1 (i = 1{,}2), d = 0.5,\ p_{b_2} = 2, p_{c_2}$=1,$c_{m_2} = 1, c_{r_2} = 1, c_1 = 1, b = 1$.

As indicated in Table 2, in the NG mode, the price of green raw materials is less than the price of green products. Moreover, the profit of the manufacturer is less than the profit of suppliers.

**Table 2.** Sensitivity analysis for scenario 1under government intervention

| NO. | $t_g$ | $w_g^*$ | $p_g^*$ | $\pi_s^*$ | $\pi_m^*$ |
|---|---|---|---|---|---|
| 1 | -4 | 6.45 | 5.02 | 2.13 | 2.06 |
| 2 | 1 | 5.41 | 5.99 | 2.28 | 2.13 |
| 3 | 2 | 5.66 | 6.19 | 2.32 | 2.15 |
| 4 | 3 | 5.61 | 6.34 | 2.36 | 2.17 |
| 5 | 4 | 5.46 | 5.56 | 2.40 | 2.19 |
| 6 | 5 | 5.31 | 6.12 | 2.44 | 2.21 |
| 7 | 10 | 4.56 | 7.73 | 3.50 | 2.23 |
| 8 | 11 | 4.20 | 6.39 | 3.59 | 3.23 |
| 9 | 12 | 5.01 | 6.59 | 3.68 | 3.3 |
| 10 | 15 | 6.02 | 6.11 | 3.78 | 3.33 |

As indicated in Table 3, in the NH mode, the price of raw material for green and non-green, the price of green and non-green products, and the profit function of supplier and manufacturer are increased. The price of raw material for NGPs and the price of NGPs are less than the price of raw material for GPs and the price of GPs. Moreover, the profit of the manufacturer is less than the profit of the supplier. Also, increasing $t_g$, in the second scenario causes an increase in the price of GPs and NGPs, price of raw material for GPs and NGPs and the profit function of the supplier and the manufacturer.

**Table 3.** Sensitivity analysis for scenario 2 under government intervention

| NO. | $t_n$ | $t_g$ | $w_n^*$ | $w_g^*$ | $p_n^*$ | $p_g^*$ | $\pi_s^*$ | $\pi_m^*$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | -4 | 2.02 | 4.65 | 1.77 | 3.02 | 1.13 | 1.06 |
| 2 | 1 | 1 | 2.27 | 3.91 | 2.13 | 3.99 | 1.28 | 1.13 |
| 3 | 1 | 2 | 2.32 | 3.76 | 2.21 | 4.18 | 1.32 | 1.15 |
| 4 | 1 | 3 | 2.37 | 3.61 | 2.28 | 4.37 | 1.36 | 1.17 |
| 5 | 1 | 4 | 2.42 | 3.46 | 2.35 | 4.57 | 1.40 | 1.19 |
| 6 | 1 | 5 | 2.47 | 3.31 | 2.43 | 4.76 | 1.44 | 1.21 |
| 7 | 1 | 10 | 2.72 | 2.56 | 2.79 | 5.73 | 1.70 | 1.33 |
| 8 | -4 | 1 | 2.20 | 2.20 | 0.70 | 4.39 | 1.79 | 1.23 |
| 9 | 1 | 1 | 2.27 | 3.91 | 2.13 | 4.99 | 1.28 | 1.13 |
| 10 | 2 | 1 | 2.29 | 4.00 | 2.42 | 4.11 | 1.04 | 1.02 |

As indicated in Table 4, in the third scenario in pricing strategy in CG mode, the profit function of GSC increases by decreasing $t_g$. Also, increasing $t_g$, in the third scenario causes an increase in the price of green products.

**Table 4.** Sensitivity analysis for scenario 3 under government intervention.

| NO. | $t_g$ | $p_g^c$ | $\pi_{SC}^c$ |
|---|---|---|---|
| 1 | -4 | 3.70 | 6.06 |
| 2 | 1 | 4.85 | 6.13 |
| 3 | 2 | 5.08 | 6.15 |
| 4 | 3 | 5.31 | 6.17 |
| 5 | 4 | 5.54 | 6.19 |
| 6 | 5 | 5.77 | 6.21 |
| 7 | 10 | 6.91 | 6.33 |
| 8 | 11 | 7.27 | 7.23 |
| 9 | 12 | 7.85 | 6.13 |
| 10 | 15 | 8.37 | 6.02 |

As indicated in Table 5, in the third scenario in pricing strategy in CH mode, the profit function of SC increases by decreasing $t_g$. Also, increasing $t_g$, in the fourth scenario causes an increase in the price of green and non-green products.

**Table 5.** Sensitivity analysis for scenario 4 under government intervention.

| NO. | $t_n$ | $t_g$ | $p_n^*$ | $p_g^*$ | $\pi_{SC}^C$ |
|---|---|---|---|---|---|
| 1 | 1 | -4 | 2.77 | 4.02 | 4.06 |
| 2 | 1 | 1 | 3.13 | 4.99 | 4.13 |
| 3 | 1 | 2 | 3.21 | 5.18 | 4.15 |
| 4 | 1 | 3 | 3.28 | 5.37 | 4.17 |
| 5 | 1 | 4 | 3.35 | 5.57 | 4.19 |
| 6 | 1 | 5 | 3.43 | 5.76 | 4.21 |
| 7 | 1 | 10 | 3.79 | 6.73 | 4.33 |
| 8 | -4 | 1 | 1.70 | 4.39 | 5.23 |
| 9 | 1 | 1 | 3.13 | 4.99 | 4.13 |
| 10 | 2 | 1 | 3.42 | 5.11 | 4.02 |

As indicated in Table 6, in hybrid production mode, cooperation of supplier and manufacturer has a positive effect on summation profits of SC.

**Table 6.** comparing profit functions in scenarios 2 and 4 under government intervention.

| NO. | $t_n$ | $t_g$ | $\pi_s^* + \pi_m^*$ | $\pi_{SC}^c$ |
|---|---|---|---|---|
| 1 | 1 | -4 | 2.19 | 4.06 |
| 2 | 1 | 1 | 2.41 | 4.13 |
| 3 | 1 | 2 | 2.47 | 4.15 |
| 4 | 1 | 3 | 2.53 | 4.17 |
| 5 | 1 | 4 | 2.59 | 4.19 |
| 6 | 1 | 5 | 2.65 | 4.21 |
| 7 | 1 | 10 | 3.03 | 4.33 |
| 8 | -4 | 1 | 3.02 | 5.23 |
| 9 | 1 | 1 | 2.41 | 4.13 |
| 10 | 2 | 1 | 2.06 | 4.02 |

As indicated in Table 7, in green production mode, cooperation of supplier and manufacturer has a positive effect on profits of SC.

**Table 7.** comparing profit function in scenarios 1 and 3 under government intervention.

| NO. | $t_n$ | $t_g$ | $\pi_s^* + \pi_m^*$ | $\pi_{SC}^c$ |
|---|---|---|---|---|
| 1 | 1 | -4 | 4.19 | 6.06 |
| 2 | 1 | 1 | 4.41 | 6.13 |
| 3 | 1 | 2 | 4.47 | 6.15 |
| 4 | 1 | 3 | 4.53 | 6.17 |
| 5 | 1 | 4 | 4.59 | 6.19 |
| 6 | 1 | 5 | 4.65 | 6.21 |
| 7 | 1 | 10 | 5.73 | 6.33 |
| 8 | -4 | 1 | 6.82 | 7.23 |
| 9 | 1 | 1 | 6.98 | 6.13 |
| 10 | 2 | 1 | 7.11 | 6.02 |

Fig. 3 shows the effect of parameter tariffs on the price of raw green material and the price of GP. Fig. 4 illustrates the effect of parameter tariffs on the profit function of supplier and manufacturer in the first scenario. As indicated in Fig. 3, the profit function of manufacturer is less than the profit function of the supplier. increasing $t_g$ in the first scenario causes an increase in the profit function of the supplier and the manufacturer in GSC. Moreover, As indicated in

Fig. 4, increasing $t_g$ in the first scenario causes an increase in the price of green products and the price of raw materials for GPs.

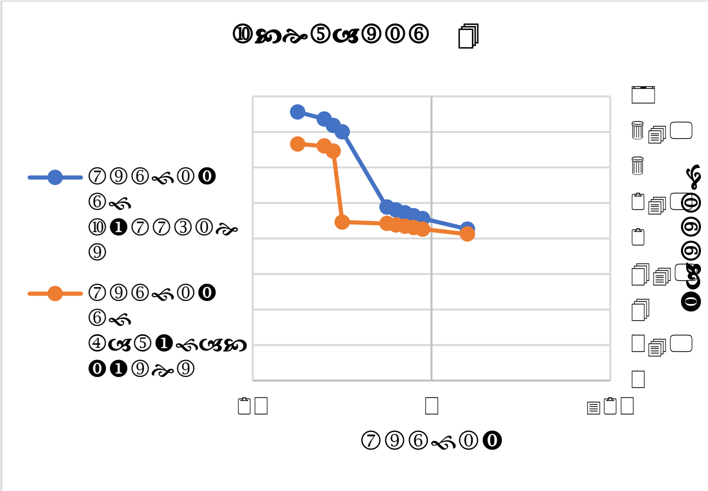

**Fig. 3.** The effects of parameter tariffs on price in scenario 1

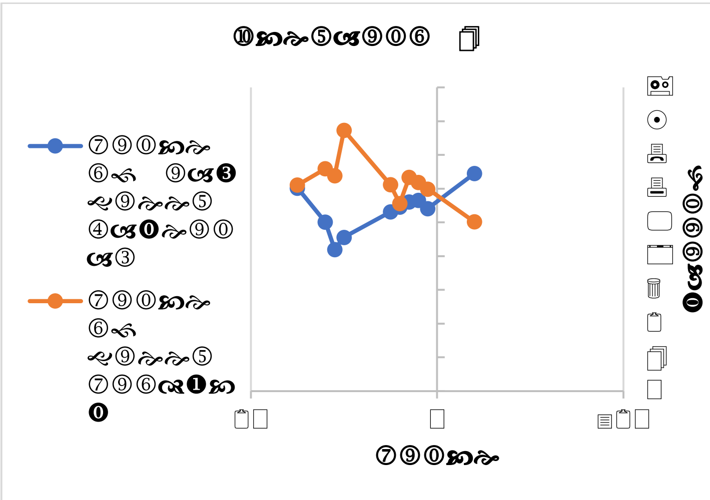

**Fig. 4.** The effects of parameter tariffs on profit in scenario 1

Fig. 5 shows the effect of parameter tariffs on the price of raw green material, price of raw non-green material, price of GP, and price of NGP in the second scenario. Fig 6. illustrates the effect of parameter tariffs on the profit function of supplier and manufacturer in the second scenario. As indicated in Fig. 5, the profit function of manufacturer is less than the profit function of the supplier. Increasing $t_g$ in the second scenario causes an increase in the profit function of the supplier and the manufacturer in GSC. As indicated in Fig. 6, the price of raw material for GPs is higher than the price of raw material for NGPs. Increasing $t_g$ in the second scenario causes an increase in the price of GPs and NGPs.

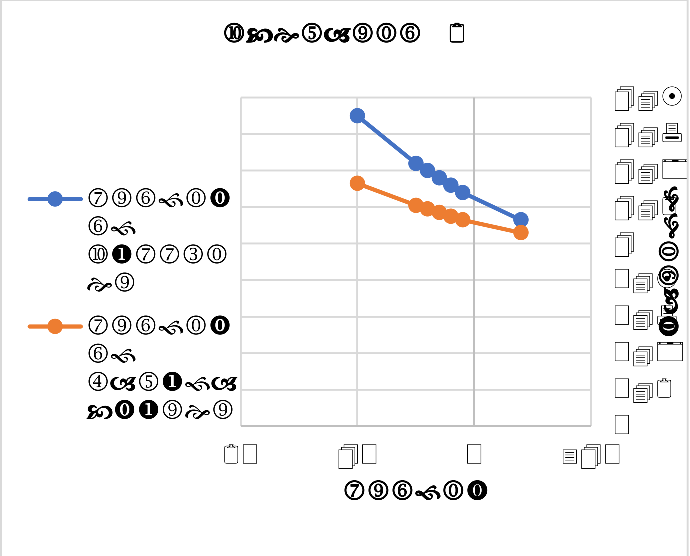

**Fig. 5.** The effects of parameter tariffs on price in scenario 1

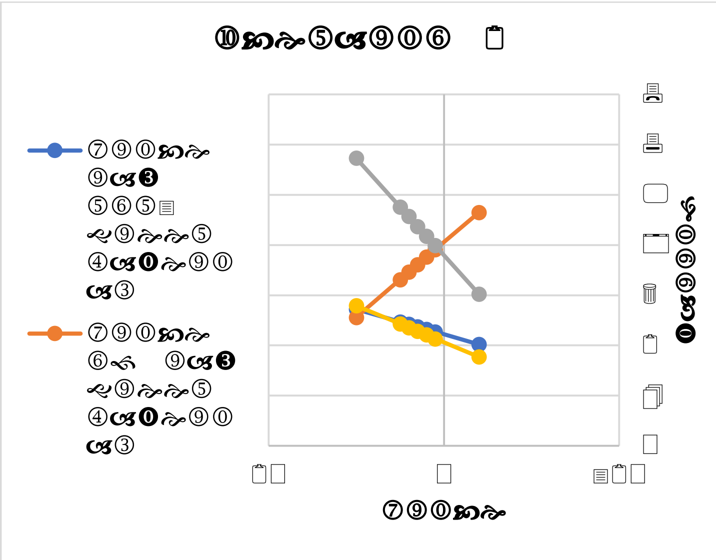

**Fig. 6.** The effects of parameter tariffs on profit in scenario 1

Fig. 7 illustrates the effects of parameter tariffs on the profit in scenarios 1 and 3. The summation of profit of the manufacturer and the supplier is greater than the profit of GSC in centralized scenarios. So, the cooperation of the supplier and the manufacturer positively affects the profit of SC.

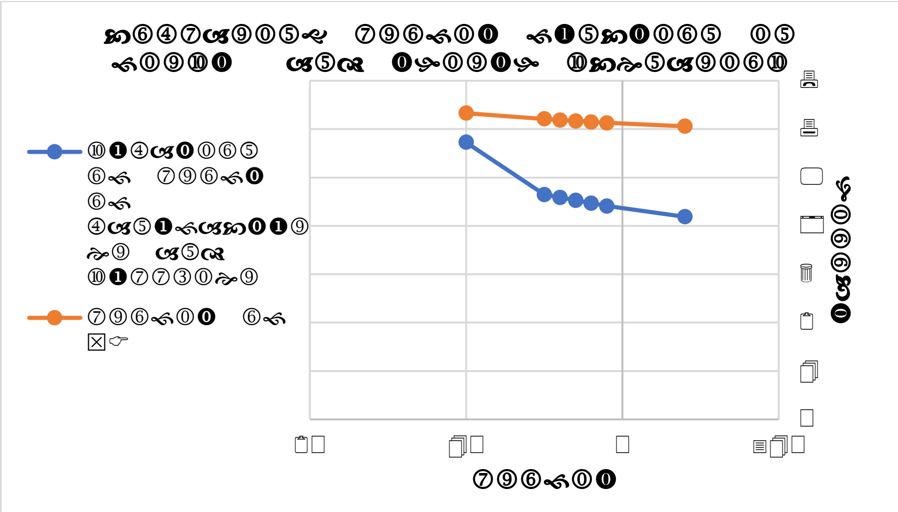

**Fig. 7.** Comparing profit function in scenarios 1and 3 under government intervention.

Fig. 8 shows the effects of parameter tariffs on profit in scenarios 2 and 4. The summation of profit of the manufacturer and the supplier is greater than the profit of GSC in centralized scenarios. So, the cooperation of the supplier and the manufacturer positively affects the profit of SC.

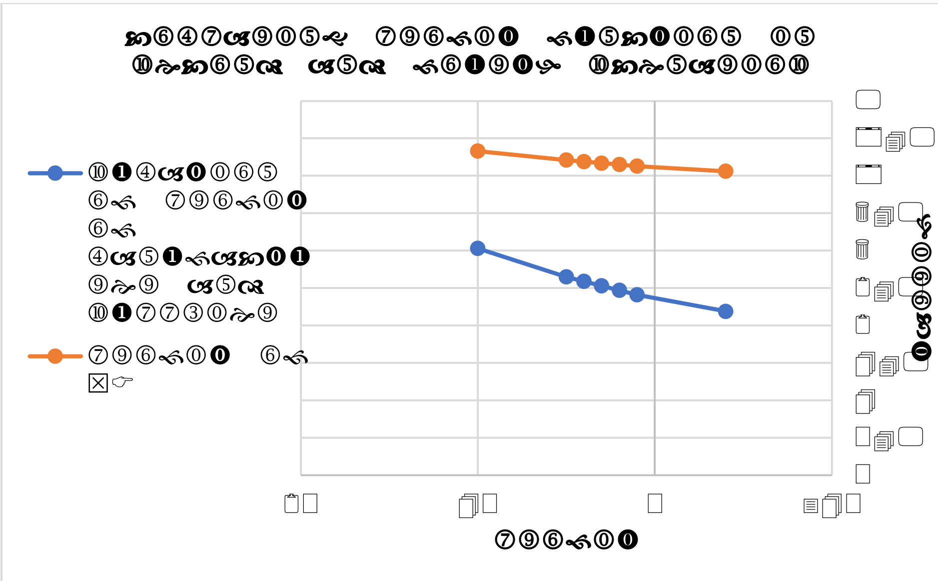

**Fig. 8.** Comparison of profit function in scenarios 2 and 4 under government intervention.

## Managerial insight

The main managerial insights extracted from this research are as follows:

- Cooperation of the supplier and the manufacturer positively affects on the profit of SC in hybrid production cases.
- Cooperation between the supplier and the manufacturer positively affects on the profit of SC in a single production mode.
- Increasing $t_g$ by government causes an increase in summation profit function of GSC and profit function of a member of GSC.
- Proposed tariffs affect the price and market demand.

- The profits in the centralized SC in hybrid and single production cases are higher than the profits in decentralized SC.
- When the government proposes a tax on NGPs, the profit function of SC in a centralized scenario decreases in hybrid production cases.
- By choosing hybrid production mode, the profit of SC decreases and hybrid production mode has not positive role on the profit of SC and membership.
- Various consumer's priorities are covered in hybrid production mode.
- If the parameter $t_g$ decreases by the government, the buyers' demand for green production increases.
- By decreasing $t_g$ by the government, the demand for non-green products increase.

## Conclusions

In this article, a green supply chain with a hybrid production mode under government intervention is considered. We investigated four scenarios based on SC structure and production mode. All results have a dramatic correlation with production modes of products. Ideal solutions for all scenarios were obtained. We found the ideal price of green and non-green raw materials, the ideal price for green and non-green products, demand, and the profit for all members in each scenario. A numerical example illustrated the results of the model. The government can guide the demand by fixing tariffs for green and non-green products.

The results showed that the members of the SC can manage costs to increase/decrease the demand of NGPs and GPs. Moreover, the government can encourage buyers to buy green products by fixing subsidies for green products and proposing taxes for non-green products. In this article, for the first time, we developed an integrated model that simultaneously considers the GCS with hybrid production mode and the competition between the members of the GSC. Through a sensitivity analysis, the effect of each parameter was investigated. The main results are as follows:

- Consumer's priorities can be satisfied by hybrid production mode.
- The cooperation of the manufacturer and the supplier can increase the profit of the GSC.
- Government policies like tariffs are efficient to decrease/ increase the price and demand of the market for green and non-green products.
- Hybrid production mode has a positive role on participating enterprises.

Some suggestions for future works are as follows: Considering the costs of maintenance and advertising for green products, applying inadequate information in the model, and generalizing various products which can change the model formulations and their responses. Also, mechanism design might be appropriate for studying the structure of the model to access new equilibrium.

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