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SUSTAINABLE AUTOMOTIVE SUPPLY CHAIN IN THE PRESENCE OF DISRUPTION AND GOVERNMENT INTERVENTION

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Abstract. This paper aims to develop and simulate a green automotive supply chain model (ASC) consisting of one supplier, one manufacturer, and two types of products (green and non-green) under disruption risks (DRs). The greening effort (*i.e.*, electric vehicle production) is considered for both the supplier and the manufacturer. In our modeling, we include the local government intervention (GI) and their incentivization of manufacturers to produce greener products. Moreover, the effectiveness of centralized *versus* decentralized supply chain integration strategies in coping with disruption consequences was explored. A mathematical pricing model based on game theory is designed to maximize the total profit for both integrated and decentralized systems. The model examines the effects of the greening effort on the supply chain (SC) members with eight disruption scenarios, including Extra Production and Surplus Inventory. Simulating numerical examples reveals that the Extra Production type of disruption increase the profitability in different scenarios. Conversely, the Surplus Inventory disruption reduces profitability. Moreover, a channel coordination through cost sharing contract in the presence of disruption sharing was developed. GI and the cost-sharing contract increase the SC profit. The managerial implications of our findings are also discussed in this paper.

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1. Introduction

Over the last two decades, trades have grown significant interest and shifted towards globalization, with a growing number of suppliers, manufacturers, and retailers from different countries being highly engaged in cross-border partnerships. While such collaboration is effective in general, any disruption, such as natural disasters or widespread disease in any region of the world, can significantly affect other parties not necessarily based in the same location [7, 20–22, 34]. In addition to natural disasters, increased uncertainties and complexities can also lead to disruptive events within/across supply chains (SCs), which in turn imposes additional risks such as financial and operational risks [20,25,37]. Given the sheer size, such disruption and its negative consequences are more apparent in more extensive and more powerful SCs, including the automotive industry, due to the high level

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of SC integration. For example, a significant disruption in Japanese car manufacturers such as Toyota, Honda, Opel, Nissan, Mitsubishi, and Daihatsu resulted in a substantial production line freeze, with losses of US$72 million a day immediately following a natural disaster (*i.e.*, the earthquake) back in 2011 [1, 3]. Following this natural disaster, the total production of Toyota and Honda decreased by >60%, Nissan, Mazda, and Daihatsu by >50%, and Mitsubishi by 25% compared to the previous period [29]. More recently, the outbreak of COVID-19 has disrupted the SCs of major car makers such as BMW, Daimler, Mercedes, and Landrover. Any disruption can damage the exchange relationship between suppliers and manufacturers, causing significant problems for both suppliers and manufacturers. However, effective control of such disruptions could reduce the total costs of disruption by about 8–14% for a given SC [41]. As such, it is critically important to identify appropriate ways to deal with a disruption in a SC. Therefore, we intend to study how disruption affects the partnership across the SC with a specific focus on the car manufacturing industry and critically assess the optimal decision-making strategies of each player in such chains. In doing so, we examine the simultaneous effect of various factors such as the party's political tie and cooperation with the government, the party's emphasis, and focus on producing a particular type of product (such as a green product) in maintaining the market share. We also scrutinize the importance of being part of a global *versus* a local SC. In the following paragraphs, the relevance and importance of each of mentioned factors are justified.

In recent years, due to the significant impact of car emissions on global climate change, growing attention has been paid to the production of green cars [5, 12, 27]. According to the European Union, 15% of carbon dioxide emissions come from passenger cars. Accordingly, due to the increased public awareness of environmental concerns, many car manufacturers have shifted their focus to producing green cars alongside their regular cars. The rise and significant success of electric automobile companies such as Tesla, Karma, and Lucid have pushed many traditional car manufacturing giants such as Toyota, Volkswagen, and Ford to shift towards the production of green cars as a strategic move in regaining their competitive advantage in the market, which prevents them from bankruptcy in such crowded market. Given the consumers' growing interest in green cars, we hypothesize that during the SC disruption, auto manufacturers should invest more in the production of green cars over regular cars to maintain their market share and survive in the turbulent market.

In addition to the increasing consumers' demand for green cars, local governments' regulations, and their incentives, further motivate car manufacturers to consider the production of green cars ([8]). For example, the US government has enacted laws, including taxes and subsidies for automakers to produce green cars. In a similar vein, the South Korean government has supported Hyundai in developing a new engine with low fuel consumption [39]. Similarly, using the Chinese government's support, BYD, Great Wall, and Geely have all introduced new eco-fuel cars to the market [9]. Local governments' support in producing green cars can be justified because of reducing environmental pollution and increasing public satisfaction. In such settings wherein the main focus of consumers is on green cars, any SC disruption that can affect the production of green cars can also challenge the manufacturer–consumer relationship and may lead to consumer dissatisfaction. Accordingly, we hypothesized that during a disruption, investing in green car production and offering it at a lower price to the market can significantly increase customer satisfaction. As such, in a disruption, the government can cooperate with the car manufacturer to produce green cars to enhance consumer satisfaction.

Given the significance of green production and the government's role in incentivizing manufacturers toward the production of green products, the automotive industry as a whole is known for its fierce competition worldwide. Immersed competition exerts excessive pressure on manufacturers, leading to irreparable damage and significant loss of market share if they are unable or not competent in managing turbulent conditions [30]. A key factor playing a role in how car manufacturers can cope with unprecedented disruption events is the extent to which they are tied to the local *versus* global partnership within their SC. If members of a car manufacturer's SC are all based within the same country, crises occurring in other parts of the world are likely to have a minor or almost negligible impact on the chain's performance and cannot impose a major risk. However, we propose that where the SC is expanded globally (*e.g.*, Toyota and Nissan), there are significant risks and performance implications in the event of a disruption, even if such disruption is local and not a global pandemic. As such, one of the most critical decisions in an automotive SC (ASC) is to decide whether to go for a centralized or a decentralized system, knowing that chain failure is inevitable.

Given that the automotive industry is a large and oligopolistic industry with a huge number of actors, the high number of players in this industry has caused major competition among suppliers to gain a more significant market share. As such, suppliers often ought to make essential decisions in different situations to meet customer demand with the sole aim of surviving in this competitive environment. This study is therefore designed to explore two key issues in the ASC: members' ability and their strategic approach to cope with disruption and the extent to which they should invest in green vehicle production to meet the market demand. The ability to make strategic decisions in the event of disruption is one of the critical success factors for car manufacturers. On the one hand, if a car manufacturer fails to cope with these conditions, the company goes bankrupt.

On the other hand, due to public demand and government incentives, car manufacturers are required to produce green cars to survive in a competitive market. Thus, this study is designed to examine the impact of disruption in the SC on the pricing of the produced cars and to study how introducing green products can affect the profitability of a car manufacturer. We also investigate how government intervention (GI) in the form of offering incentives can influence car manufacturers' greening efforts and aim to identify the optimum combination of price and greening efforts. Our study further attempts to unveil and explain how channel coordination through costs contract motivates SC members to participate in SC cooperation.

In presence of mentioned conditions, the following questions are raised:

– What is the effect of introducing a green product on profitability?
– What is the effect of disruption in the supply chain on the pricing of products?
– What is the effect of government intervention on greening efforts?
– What is the optimum combination of price and greening efforts?

Our study, therefore, makes at least the following contributions. First, we are developing a disruption model to investigate the effects of the various kinds of disruption on demand for green and non-green products in an ASC. Second, we develop and run a mathematical model under eight different disruption scenarios and compare them with non-disruption systems. Third, we compare the performance and effectiveness of centralized *versus* decentralized SC integration strategies in the event of a SC disruption. Fourth, we analyze the effect of GI in the ASC in dealing with disruption. Finally, we consider channel coordination through the cost-sharing contract in the presence of disruption to attract downstream supply entities of the SC to act in the model.

The methodology of the model is as follows: Using a quantitative research approach, this work studies a two-stage ASC coordination. First, a mathematical model has been developed based on real world observations. The profit function has been extracted for each member of the supply chain in the presence of disruption, and also without disruption. Then, using mathematical methods, the model is solved parametrically in both Nash ans Stackelberg game, where both of centralized and decentralized models and also the disruption status are considered. Moreover, the GI and channel coordination through the cost-sharing contract in the presence of disruption is developed.

Noteworthy, while very few studies have considered the ASC as the context for a game model in the pertinent literature, they are very different in terms of structure, method of conceptualization, and approach to modeling. Zhao *et al.* [44], Hadi *et al.* [16], and Fander and Yaghoubi [10] are among few studies examining the relationship between the members of an ASC using a game theory perspective. Yet, none of these studies explored the impact of disruption on the decisions of ASC members. To the best of our knowledge, this article is the first to address decision-making in disruptive situations, ways to deal with it, and government support for auto manufacturers to overcome it. Our study looks into the relations and factors within an ASC in the presence of a disruption. In our models, GI aims to incentivize green product development by ordaining the subsidiary taxation policy. The simultaneous impact of these factors and the cost-sharing contract for cooperation are considered in our model development and simulations.

The remainder of this article is organized as follows: Section 2 briefly reviews the related literature. Section 3 explains the formulation of the model without disruption and GI impacts. In Section 4, GI in green products in the presence of disruption is added to the model formulated in Section 3. In Section 5, the channel coordination through a cost-sharing contract is added to the model in Section 4. Section 6 contains some numerical examples, and Section 7 represents the sensitivity analysis. Section 8 includes some managerial insights, and finally, Section 9 represents the conclusions.

2. Literature review

This research is related to three different literature areas: disruption, ASC, and GI in the green SC.

2.1. Disruption in Supply Chain

In the area of the SC, some researchers considered the disruption issue. Arto *et al.* [1] evaluated the global economic effects of disruptions in ASCs, which were affected by the Japanese earthquake and the consequent tsunami of 2011. After Tohoku Earthquake in 2011, Matsuo [29] considered disruption in automotive microcontroller units of the Toyota SC. Simchi-Levi *et al.* [35] investigated risks and mitigating disruptions in Ford Motor Company. Zhang *et al.* [43] investigated the DR of the supplier in the Chinese ASC, where two downstream members are considered. Ghavamifar *et al.* [14] developed an intra-SC competition using a bi-level multi-objective programming approach to consider the uncertainties and DRs. Furthermore, Vanalle *et al.* [36] investigated risk management in the ASC, where their focus is in Brazil. Kasim *et al.* [24] investigated disruption in the material supply of an ASC.

Some researchers have addressed disruption in the context of the green SC. Rahmani and Yavari [32] considered the pricing and also greening issues in a dual-channel green SC when the disruption is affected by market demand. Yavari and Zaker [38] studied a resilient-green closed-loop SC with perishable products in the presence of DRs. Li and He [26] considered disruption in a green SC in which the manufacturer sells green products to customers *via* an online channel. They investigate information disclosure and price compensation strategies to cope with a green production break. Aslani and Heydari [2] considered greening effort, pricing, and coordination in a dual-channel SC, where the SC faces channel disruption.

Although the effects of various disruption types have been studied in the literature till now, the emerging COVID-19 disruption has yet to be investigated. Here, we examine the COVID-19 disruptive effects on SCs.

2.2. Automotive Supply Chain

Although ASCs have been more considered in the literature in the last decade, few studies have focused on the pricing of ASCs *via* the game theory approach. Biller *et al.* [6] investigated a model to optimize the coordination between production and inventory decisions, where a greedy algorithm was developed. Olugu *et al.* [31] investigated some measures to evaluate the performance of the automobile green SC. As technology is one of the most significant issues in the automotive industry, Jun and Park [23] analyzed the technological competition between car manufacturers (Hyundai and BMW) based on their technologies. Using a statistical model, they found the effect of technologies for each brand on its market demand. Hadi *et al.* [16] developed a dual-channel green car SC with two substitutable products. To control the SC, the government pays some kinds of tariffs. Zhao *et al.* [44] considered a Chinese closed-loop SC for new energy cars, where there are government subsidies. Using a game model of the pricing and the efficiency of the energy level in the ASC, Rasti-Barzoki and Moon [33] considered the government sustainability goals and its intervention in the vehicle and fuel SCs. They implemented their research in the South Korean market. They found that by using government support, the vehicle manufacturers reduced the fuel consumption of the vehicles, and hence, they could develop more fuel-efficient vehicles for the market. Considering GI and carbon emission reduction, Ma *et al.* [28] investigated a mathematical model for an electric vehicle manufacturer. Ma *et al.* [28] developed a coordination model for china's ASC, where new energy vehicles are considered based on a dual-credit policy. Furthermore, Fander and Yaghoubi [10] studied an automotive green SC next to a fuel SC, which both operate under GI. They supposed that the demand was stochastic, and there was demand leakage.

This research addresses the pricing of two product types (green and non-green) in the ASC, considering disruption and GI. Although GI and disruption both influence demand, the effect of disruption in the presence of GI has yet to be studied in green SC literature. Moreover, the impact of cost-sharing using sharing contracts is investigated.

2.3. Government Intervention in the Green Supply Chain

GI has a motivational and supportive tool for organizations and customers in the SCs discussed in the literature. Hafezalkotob [17] developed a price competition model for a green SC in which the government financially intervenes. The model considered six scenarios based on government tendencies and decision-making structures of the SC. The model investigated the impact of the government's tariffs on the optimal strategies of the SC members. Hafezalkotob [18] examined the equilibrium between green and non-green products *via* a game theory model, considering different GI types. Furthermore, Zhang and Yousaf [42] evaluated the coordination in a green SC, where the government intervenes in the market. Moreover, Gao *et al.* [13] developed a dual-channel SC. The government defines a green standard for the manufacturer and has an eco-label policy for green products. Developing a game theory model, Gorji *et al.* [15] considered the end-of-life vehicle reverse SC when the government subsidizes the manufacturers. They also developed two contracts (profit sharing and revenue sharing).

Although GI has been addressed in the literature, the economic and social impact of this variable on ASCs has yet to be studied (in the form of tax and subsidy) simultaneously. Therefore, the mentioned gap is a suitable ground for this research.

2.4. Research gaps

This research evaluates SC coordination in a two-stage automotive chain alongside GI and disruption. In the real world, market conditions are changing due to different social, economic, and political disruptions. Hence, the SCs should manage the disruptions to be survived. Given that the ASCs deal with government supervision in the oligopoly vehicle markets, this space is highly influential in the decisions of SCs. However, the existing literature on ASCs and disruption in a sustainable SC has not addressed the combination models of disruption in a sustainable SC and GI. Table 1 represents the differences among the most similar studies with the current paper. As it is illustrated in Table 1, none of the studies has addressed the ASC coordination considering disruption and GI. This issue has been considered for the first time in the present research.

Although some researchers have considered sustainable ASCs, none of them has investigated the disruption in a sustainable SC and the GI simultaneously. This research considers demand disruption and GI effects on a sustainable ASC for the first time.

3. Problem description

A two-stage ASC comprising one supplier and one manufacturer which produces two substitutable products (Green and Non-Green) in an oligopolistic market is considered. The supplier supplys all parts of both products to the manufacturer producing products. The greening effort is considered for both the supplier and the manufacturer. Due to the cost of greening efforts, the price of this product is higher than the non-green one. The disruption can affect both the supplier and the manufacturer sides. Here, two kinds of disruption were considered; Extra Production and Surplus Inventory. Moreover, disruption in situations such as pandemics for both manufacturer and supplier affects the demand and supply values of manufacturer and supplier, respectively. Both integrated and decentralized systems are investigated and compared. Consider a situation in which all SC members are inside a country, and disruption disrupts cross-border transport activities. Hence the goods movement from the supplier to the manufacturer will be done in time. If some competitors may have one of their SC members abroad and have problems transferring goods, then the demand for the SC would increase. In this situation, the demand would increase, creating a need for extra production. Conversely, if some of the SC members are outside the country in case of such disruption, then the movement of goods may face problems.

Table 1. A brief comparison of current research with the most relevant studies.

Authors	Supply chain: Automotive	Supply chain: Sustainable	Supply chain: Others	Pricing	Disruption	Government Intervention	Contract
Matsuo [29]	•	•			•		
Arto *et al.* [1]	•				•		
Hafezalkotob [17]		•		•		•	
Rahmani and Yavari [32]		•	•	•	•		
Rasti-Barzoki and Moon [33]	•	•		•		•	
Hadi *et al.* [16]	•	•		•		•	
Zhang and Yousaf [42]		•		•		•	Two-part tariff
Zhao *et al.* [44]	•	•		•		•	
Ma *et al.* [28]	•			•		•	
Gorji *et al.* [15]	•					•	Profit-sharing/Revenue-sharing
Fander and Yaghoubi [10]	•	•				•	
Current Study	•	•		•	•	•	Cost-Sharing

To tackle such disruption, having a surplus inventory would be beneficial; otherwise, the demand can not be fulfilled completely. Moreover, GI is exerted through subsidy-taxation policy. The government subsidizes the manufacturer to make developing the green product profitable. On the other hand, the government receives some portion of the manufacturer's income as tax to increase both the economic and the social utilities. The government plays the role of leader, whereas the manufacturer acts as a follower. Moreover, the manufacturer plays the role of a leader for the supplier. To convince the SC members to act coordinately, a cost-sharing contract between the manufacturer and the supplier is beneficial. Hence, the channel coordination through the cost-sharing contract in the presence of disruption is developed.

A mathematical model has been developed, using a quantitative research approach. The model is solved parametrically in both Nash and Stackelberg game, where both of centralized and decentralized models and also the disruption status are considered. In Stackelberg model, the manufacturer plays the role of leader, while the supplier is known as a follower. It means that the power of the manufacturer is higher the supplier. Moreover, in Nash model, the power of both manufacturer and the supplier is qual.

Figure 1 represents a schematic view of the developed model. The manufacturer aims to maximize its profit by adjusting the greening efforts, as well as pricing policies. Furthermore, the supplier endeavors to optimize its profit *via* greening efforts for the green parts.

All the notations used in model development are represented in Table 2.

The primary assumptions of the model are demonstrated as follows:

(1) The whole market demand of the ASC described above is comprised of two parts; Green and Non-Green products. All parts of the demand are deterministic. Furthermore, four endogenous decision variables affect the demand for both green and non-green products (P_1, P_2, θ, and φ). In this study, the demand functions of green products and non-green products are similar to what Rahmani and Yavari [32] used in their research (Eqs. (1) and (2)).

$$D_1 = a_1 - \beta_1 P_1 - \rho_1(P_1 - P_2) + \gamma_1\theta + \lambda_1\varphi \tag{1}$$

$$D_2 = a_2 - \beta_2 P_2 - \rho_2(P_2 - P_1) - \gamma_2\theta - \lambda_2\varphi \tag{2}$$

where β_i, ρ_i, γ_i, and λ_i are positive coefficients.

TABLE 2. Notations.

Subscripts	
I	Integrated system
D	Decentralized system
E	Extra production
S	Surplus inventory
co	Cost-sharing contract
Parameters	
D_i	The demand for product i, $i=1,2$ (Green and Non-Green, respectively)
$\overline{D}_i^{rk}$	The demand for the product i in the presence of disruption, $i=1,2$, $r=I,D$, $j=E,S$
$\overline{D}^j$	The total demand for products 1 and 2 in the presence of disruption, $r=I,D$, $j=E,S$
Q_r^*	Production quantity in the presence of disruption, $r=I,D$
a_i	Market potential demand for the product type i, $i=1,2$
Δa_i^{rj}	The increase/decrease in the market potential demand for the product i due to disruption, $i=1,2$, $r=I,D$, $j=E,S$
W_i	Purchasing price of product i from the supplier by the manufacturer, $i=1,2$
$\overline{W}_i^{re}$	Purchasing price of product i from the supplier by the manufacturer, $i=1,2$, $r=I,D$, $j=E,S$
C_i	The production cost of product i for the supplier
$\overline{C}_i^{rj}$	The production cost of product i for the supplier considering disruption, where $i=1,2$, $r=I,D$, $j=E,S$
A_i	Manufacturer general and administrative cost of product i, $i=1,2$
δ	Government intervention level
E_k^r	The unit cost imposed by the Extra Production scenario, where $k=m,s,c$ and $r=I,D$
S_k^r	The unit cost imposed by the Surplus Inventory scenario, where $k=m,s,c$ and $r=I,D$
Ω	The ratio of cost imposed on the supplier in the contract
F	Franchise parameter
β_i	Price sensitivity coefficient of product type i, $i=1,2$
ρ_i	Price-competitive sensitivity coefficient of product type i, $i=1,2$
γ_i	Sensitivity coefficient of the greening level for products type i produced by the manufacturer, $i=1,2$
λ_i	Sensitivity coefficient of the greening level for parts of the product's type i supplied by the supplier, $i=1,2$
τ	The cost coefficient of the greening level of the product type 1 produced by the manufacturer
h	The cost coefficient greening level of the parts of product type 1 supplied by the supplier
ζ_1	The economic utility of government
ζ_2	The social utility of government
S'	The utility coefficient of the greening level for both green products and green parts for the government
Decision variables	
P_i	The sales price of product type i, $i=1,2$
$\overline{P}^{ark}$	The sales price of product type i considering disruption, where $i=1,2$, $r=I,D$, $j=E,S$
θ	Greening level of product type 1 (Green Product) produced by the manufacturer
$\overline{\theta}^{rj}$	Greening level of product type 1 produced by manufacturer considering the disruption
φ	Greening level of the parts of product type 1 (Green Parts) supplied by the supplier
$\overline{\varphi}^{rj}$	Greening level of the parts of product type 1 supplied by supplier considering disruption, where $i=1,2$, $r=I,D$, $j=E,S$
Profit function	
$\overline{\Pi}_k^{rj}$	Profit function considering disruption rj, where $r=I,D$, $j=E,S$, and $k=m,s,c$
$\overline{\Pi}^{rj}$	Profit function of Integrated system considering disruption rj, where $r=I,D$, $j=E,S$, and $k=m,s,c$
$\overline{\Pi}_k^{rj^*}$	Profit function considering disruption rj and government intervention, where $r=I,D$, $j=E,S$, and $k=m,s,g$
$\overline{\Pi}_k^{co-RJ}$	Profit function considering contract and disruption, where $r=I,D$, $j=E,S$, and $k=m,s,c$
T_i	Substituted Variables which are described in Appendix A, $i=1-36$

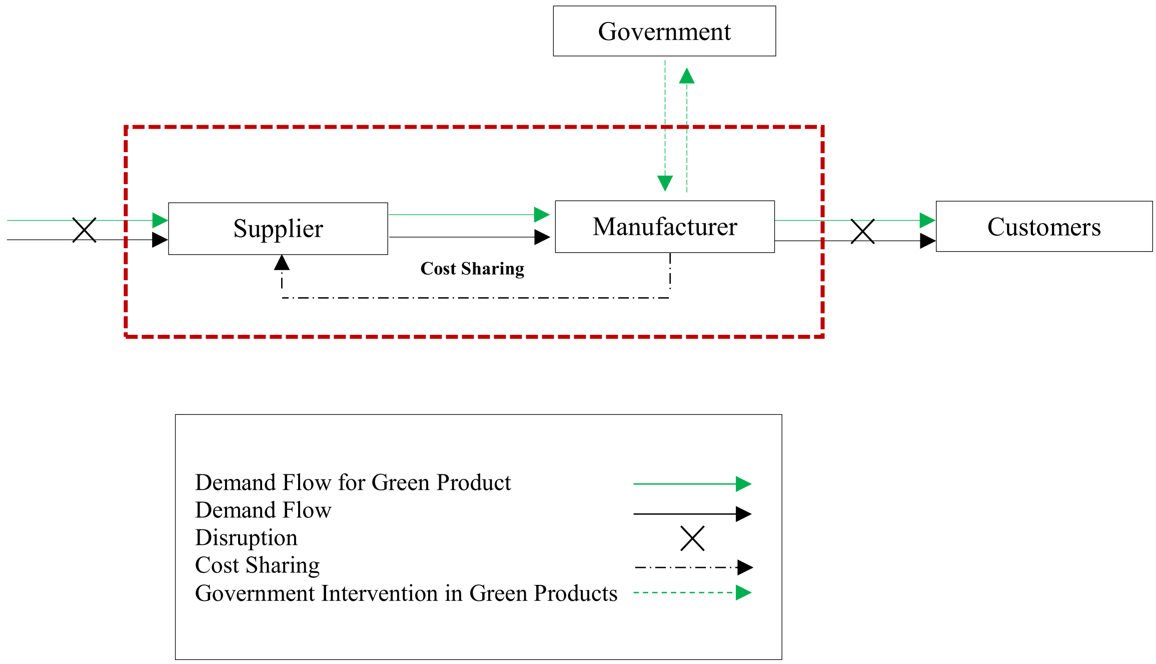

FIGURE 1. Model representation.

(2) In case of decreasing the greening level of product type 1 produced by the manufacturer (green product), some portions of its demand are transferred to product type 2 (non-green product [4]).
(3) To formulate the costs related to the greening level of the green product (produced by the manufacturer), as well as the greening level of the green parts (supplied by the supplier), a quadratic relation is exploited, which has been employed by several researchers in the literature.
(4) All the demands of customers may not be satisfied due to disruption. Hence, the shortage is allowed [32].
(5) The government intervenes through two approaches; subsidizing the manufacturer to support producing green products and receiving income tax. This could be observed in some oligopolistic automotive markets with limited numbers of significant players in some countries [11].
(6) The disruption can cause a decrease or increase in customer demand. On the other hand, disruption may disarrange the supply to the manufacturer due to several possible factors such as governments' decisions or road closures. This leads to a highly limited supply and, in turn, a need for more customer demand [29].
(7) Channel coordination through a cost-sharing contract is considered, which lets the supplier share its costs with the manufacturer, which leads to an increase in the profitability of both members (supplier and manufacturer).
(8) The price sensitivity coefficient of product type i (β_i) is higher than the price-competitive sensitivity coefficient of product type i (ρ_i) [17].

The manufacturer decides on the greening level (θ) of product type 1 (Green Product) and the sales price of both product types (P_1 and P_2), while the supplier decides on the greening level of the parts of product type 1 supplied by the supplier (Green Parts) (φ).

The primary difference between the two types of products is the greening level on both parts supplied by the supplier and both products manufactured. Green products are less harmful to the environment. No greening efforts are made for non-green products. Also, greening efforts are considered on both the supplier and manufacturer sides. In the supplier, the greening efforts are applied to components, while the greening efforts are exploited to the green product through the manufacturing processes.

Based on the COVID-19 pandemic experiences, two kinds of disruption are considered; with a disruption in supply and without a disruption in supply. When the disruption in the SC does not affect the supply, maybe because of using a domestic supplier, the supply process will not experience a disturbance, and the production process can smoothly continue. This is regarded as a superiority of this SC over those with suppliers affected by the disruption. On the other hand, if the disruption brings the supplier unpredictable obstacles, the production process will not go on smoothly, and the predicted demand cannot be completely fulfilled.

In this paper, a game approach is applied to investigate an oligopolistic condition of the automotive industry, where the government intervenes in green products through the subsidiary-taxation policy, which aims to support producing green products. The following sections examine the model in decentralized and integrated systems, where non-disruption and disruption scenarios are examined.

3.1. Non-Disruption scenarios

In this section, non-disruption scenarios (NDS), including decentralized and integrated systems, are examined.

3.1.1. Decentralized system of NDS

In this section, a Stackelberg scenario is developed, where the manufacturer and the supplier tend to maximize their profit, which could conflict. It is assumed that the manufacturer plays the role of leader, and the supplier is known as a follower. The manufacturer decides on P_1, P_2, and θ, while the supplier decides on φ. The profit function of the supplier of a decentralized system $\left(\Pi_s^{ds}(\varphi)\right)$ is as equation (3) (Superscription D represents decentralized considering the Stackelberg approach, where subscription s represents the supplier).

$$\Pi_s^D(\varphi) = \sum_{i=1}^{2} (W_i - C_i)D_i - h\frac{\varphi^2}{2}\cdot \tag{3}$$

In equation (3), the first and second terms indicate the supplier revenue and the cost imposed by the greening level of the product, respectively. A necessary condition for profitability is $W_i \geq C_i$.

Theorem 3.1. *The decentralized profit function of the supplier* $(\Pi_s^D(\varphi))$ *is concave in* φ*.*

Proof. By determining the second-order derivative of the profit function, a positive h obviously guarantees the concavity condition. □

Based on Theorem 3.1, the optimum greening level of the parts of product type 1 supplied by the supplier (green parts) is obtained by equation (4).

$$\varphi = \frac{C_2\lambda_2 - C_1\lambda_1 + \lambda_1 W_1 - \lambda_2 W_2}{h}\cdot \tag{4}$$

The manufacturer profit function in a decentralized system $(\Pi_m^D(P_1,\ P_2,\theta))$ is shown in equation (5) (Superscriptions D and m represent decentralized considering the Stackelberg approach and the manufacturer, respectively).

$$\Pi_m^D(P_1, P_2, \theta) = \sum_{i=1}^{2} (P_i - W_i)D_i - \sum_{i=1}^{2} A_i D_i - \tau\frac{\theta^2}{2}\cdot \tag{5}$$

In equation (5), the first clause represents the revenue of the manufacturer, and the second and third clauses state the general and administrative costs for the manufacturer, and the greening costs, respectively. To ensure the necessary condition for profitability, we have $P_i \geq W_i$.

Theorem 3.2. *The decentralized profit function of the manufacturer* $\left(\Pi_m^D(P_1, P_2, \theta)\right)$ *is a concave function if* $4\beta_1\beta_2 > (\rho_1 - \rho_2)^2$ *and* $\left(\frac{\gamma_2}{\gamma_1}\right)^2 > \frac{\rho_2 - \beta_2}{\rho_1 + \beta_1}$.

Proof. Hessian matrix (H) is as follows:

$$H(P_1, P_2, \theta) = \begin{bmatrix} \frac{\partial^2 \Pi_m^D}{\partial P_1^2} & \frac{\partial^2 \Pi_m^D}{\partial P_1 \partial P_2} & \frac{\partial^2 \Pi_m^D}{\partial P_1 \partial \theta} \\ \frac{\partial^2 \Pi_m^D}{\partial P_2 \partial P_1} & \frac{\partial^2 \Pi_m^D}{\partial P_2^2} & \frac{\partial^2 \Pi_m^D}{\partial P_2 \partial \theta} \\ \frac{\partial^2 \Pi_m^D}{\partial \theta \partial P_1} & \frac{\partial^2 \Pi_m^D}{\partial \theta \partial P_2} & \frac{\partial^2 \Pi_m^D}{\partial \theta^2} \end{bmatrix} = \begin{bmatrix} -2(\beta_1 + \rho_1) & \rho_1 + \rho_2 & \gamma_1 \\ \rho_1 + \rho_2 & -2(\beta_2 + \rho_2) & -\gamma_2 \\ \gamma_1 & -\gamma_2 & -\kappa \end{bmatrix}.$$

The first principal minor determinant of profit function (Π_m^D) is $(-2(\beta_1 + \rho_1)) < 0$. Besides, the second principal minor determinant of profit function is positive $(4\beta_1\beta_2 + 4\beta_1\rho_2 + 4\beta_2\rho_1 - \rho_1^2 + 2\rho_1\rho_2 - \rho_2^2) > 0$ and the third principal minor determinant is negative $(-4\beta_1\beta_2 k - 4\beta_1\rho_2 k - 2\beta_1{\gamma_2}^2 - 4\beta_2\rho_1 k + 2\beta_2{\gamma_1}^2 + k\rho_1^2 - 2k\rho_1\rho_2 + k\rho_2^2 - 2\rho_1\gamma_2^2 - 2\rho_2\gamma_1^2) < 0$ due to the model assumption. If assumptions hold, the Hessian matrix of profit function is negative semidefinite. □

Based on the concavity of the manufacturer profit function, a closed form for the optimum decision variables can be obtained by equations (6)–(8).

$$P_1 = \left(T_2 + h\left(\gamma_2^2\rho_1 - T_3(\beta_2 + \rho_2)\right)A_2\right)/hT_1 \tag{6}$$
$$P_2 = \left(T_4 + \gamma_1\gamma_2\left(\left(a_1 h - C_1\lambda_1^2\right) + C_2\right) + \lambda_1\lambda_2\left(C_1\left(\gamma_1^2 - 2\beta_1\tau\right)\right)\right)/hT_1 \tag{7}$$
$$\theta = (T_5 + 2\beta_1\lambda_2(C_1\gamma_2\lambda_1 - C_2\gamma_2\lambda_2) + 2\beta_2\gamma_1\lambda_1(C_1\lambda_1 - C_2\lambda_2))/hT_1. \tag{8}$$

3.1.2. Integrated system of NDS

In the integrated system, the supplier and the manufacturer have the same power to interpret these circumstances. The manufacturer and the supplier decide on P_1, P_2, θ, and φ. The profit function of the integrated system $(\Pi^I(P_1, P_2, \theta, \varphi))$ is shown in equation (9).

$$\Pi^I(P_1, P_2, \theta, \varphi) = \sum_{i=1}^{2}(P_i - C_i)D_i - \sum_{i=1}^{2} A_i D_i - \tau\frac{\theta^2}{2} - h\frac{\varphi^2}{2}\cdot \tag{9}$$

To ensure profitability, $P_i \geq C_i$ is necessary.

Theorem 3.3. *The integrated profit function of the SC* $(\Pi^I(P_1, P_2, \theta, \varphi))$ *is concave if* $4\beta_1\beta_2 > (\rho_1 - \rho_2)^2$, $h\tau > h + \tau$, *and* $\lambda_1\gamma_1 > \lambda_1^2$.

Proof. Hessian matrix (H) is as follows:

$$H(P_1, P_2, \theta, \varnothing) = \begin{bmatrix} \frac{\partial^2 \Pi^I}{\partial P_1^2} & \frac{\partial^2 \Pi^I}{\partial P_1 \partial P_2} & \frac{\partial^2 \Pi^I}{\partial P_1 \partial \theta} & \frac{\partial^2 \Pi^I}{\partial P_1 \partial \varnothing} \\ \frac{\partial^2 \Pi^I}{\partial P_2 \partial P_1} & \frac{\partial^2 \Pi^I}{\partial P_2^2} & \frac{\partial^2 \Pi^I}{\partial P_2 \partial \theta} & \frac{\partial^2 \Pi^I}{\partial P_2 \partial \varnothing} \\ \frac{\partial^2 \Pi^I}{\partial \theta \partial P_1} & \frac{\partial^2 \Pi^I}{\partial \theta \partial P_2} & \frac{\partial^2 \Pi^I}{\partial \theta^2} & \frac{\partial^2 \Pi^I}{\partial \theta \partial \varnothing} \\ \frac{\partial^2 \Pi^I}{\partial \varnothing \partial P_1} & \frac{\partial^2 \Pi^I}{\partial \varnothing \partial P_2} & \frac{\partial^2 \Pi^I}{\partial \varnothing \partial \theta} & \frac{\partial^2 \Pi^I}{\partial \varnothing^2} \end{bmatrix} = \begin{bmatrix} -2(\beta_1 + \rho_1) & \rho_1 + \rho_2 & \gamma_1 & \lambda_1 \\ \rho_1 + \rho_2 & -2(\beta_2 + \rho_2) & -\gamma_2 & -\lambda_2 \\ \gamma_1 & -\gamma_2 & -k & 0 \\ \lambda_1 & -\lambda_2 & 0 & -h \end{bmatrix}.$$

The first principal minor determinant of profit function (Π^I) is $(-2(\beta_1 + \rho_1)) < 0$. Besides, the second principal minor determinant of profit function is positive $(4\beta_1\beta_2 + 4\beta_1\rho_2 + 4\beta_2\rho_1 - \rho_1^2 + 2\rho_1\rho_2 - \rho_2^2) > 0$ and the third principal minor determinant is negative $(-4\beta_1\beta_2 k - 4\beta_1\rho_2 k - 2\beta_1{\gamma_2}^2 - 4\beta_2\rho_1 k + 2\beta_2{\gamma_1}^2 + k\rho_1^2 - 2k\rho_1\rho_2 + k\rho_2^2 - 2\rho_1\gamma_2^2 - 2\rho_2\gamma_1^2) < 0$ due to the model assumption. Furthermore, the fourth minor determinant is positive

TABLE 3. Scenarios of market potential changes and demands.

Systems	Disruption kinds		Market potential/Demand situations
Integrated	Extra Production	Δa	Δa_i^{IE}
		$\overline{D}$	$\overline{D}_i^{\mathrm{IE}} = \left(a_i + \Delta a_i^{\mathrm{IE}}\right) - \beta_i \overline{P}_i^{\mathrm{IE}} - \rho_i\left(\overline{P}_i^{\mathrm{IE}} - \overline{P}_j^{\mathrm{IE}}\right) + \gamma_i \overline{\theta}^{\mathrm{IE}} + \lambda_i \overline{\varphi}^{\mathrm{IE}}, \quad i = 1,2, i \neq j$
	Surplus Inventory	Δa	Δa_i^{IS}
		$\overline{D}$	$\overline{D}_i^{\mathrm{IS}} = \left(a_i + \Delta a_i^{\mathrm{IS}}\right) - \beta_i \overline{P}_i^{\mathrm{IS}} - \rho_i\left(\overline{P}_i^{\mathrm{IS}} - \overline{P}_j^{\mathrm{IS}}\right) + \gamma_i \overline{\theta}^{\mathrm{IS}} + \lambda_i \overline{\varphi}^{\mathrm{IS}}, \quad i = 1,2, i \neq j$
Decentrzlized	Extra Production	Δa	Δa_i^{DE}
		$\overline{D}$	$\overline{D}_i^{\mathrm{DE}} = \left(a_i + \Delta a_i^{\mathrm{DE}}\right) - \beta_i \overline{P}_i^{\mathrm{DE}} - \rho_i\left(\overline{P}_i^{\mathrm{DE}} - \overline{P}_j^{\mathrm{DE}}\right) + \gamma_i \overline{\theta}^{\mathrm{DE}} + \lambda_i \overline{\varphi}^{\mathrm{DE}}, \quad i = 1,2, i \neq j$
	Surplus Inventory	Δa	Δa_i^{DS}
		$\overline{D}$	$\overline{D}_i^{\mathrm{DS}} = \left(a_i + \Delta a_i^{\mathrm{DS}}\right) - \beta_i \overline{P}_i^{\mathrm{DS}} - \rho_i\left(\overline{P}_i^{\mathrm{DS}} - \overline{P}_j^{\mathrm{DS}}\right) + \gamma_i \overline{\theta}^{\mathrm{DS}} + \lambda_i \overline{\varphi}^{\mathrm{DS}}, \quad i = 1,2, i \neq j$

$((4\beta_1\beta_2 hk + 4\beta_1 hk\rho_2 - 2\beta_1 h\gamma_2^2 - 2\beta_1 k\lambda_2^2 + 4\beta_2 hk\rho_1 - 2\beta_2 h\lambda_1\gamma_1 - 2\beta_2 k\lambda_1^2 - hk\rho_1^2 + 2hk\rho_1\rho_2 - hk\rho_2^2 + h\lambda_1\rho_1\gamma_2 + h\lambda_1\rho_2\gamma_2 - 2h\lambda_1\rho_2\gamma_1 - 2h\rho_1\gamma_2^2 + h\rho_1\gamma_1\gamma_2 + h\rho_2\gamma_1\gamma_2 - 2k\lambda_1^2\rho_2 + 2k\lambda_1\lambda_2\rho_1 + 2k\lambda_1\lambda_2\rho_2 - 2k\rho_1\lambda_2^2 - \lambda_1^2\lambda_2\gamma_2 + \lambda_1^2\gamma_2^2 + \lambda_1\lambda_2^2\gamma_1 - \lambda_1\lambda_2\gamma_1\gamma_2) > 0)$ due to the aforementioned assumptions. Hence, the Hessian matrix of the profit function is negative semidefinite if the assumptions hold. □

Based on the concavity of the SC profit function, a closed form for the optimum decision variables can be obtained by equations (10)–(13).

$$P_1 = \left(T_6 - \gamma_2^2\left(h(a_1 + \beta_1 C_1) + C_1\lambda_1^2\right) + 2C_1\gamma_1\lambda_2(\gamma_1\lambda_2 - \gamma_2\lambda_1)\right)/T_8 \tag{10}$$

$$P_2 = T_7/T_8 \tag{11}$$

$$\theta = T_9/T_8 \tag{12}$$

$$\varphi = T_{10}/T_8. \tag{13}$$

3.2. Disruption scenarios

Due to a disruption, different scenarios might happen. We investigate two scenarios in two different systems (integrated and decentralized) (Tab. 2). Consider a situation in which total demand increases and the disturbance does not affect the supplier. In this case, Extra Production is needed to respond to market demand. The second one is a situation where the supplier is negatively influenced, and the total supply becomes limited. Therefore, SC will only respond to the demand if Surplus Inventory is employed to fulfill the supply. In Table 3, it is supposed that $\Delta a_i^{\mathrm{IE}}, \Delta a_i^{\mathrm{DE}} > 0$ and Δa_i^{IS}, $\Delta a_i^{\mathrm{DS}} < 0$, where $i = 1, 2$.

Besides the two scenarios shown in Table 3, other scenarios may occur, *i.e.*, only the manufacturer or the supplier are confronted to disruption. Moreover, in some cases, both the supplier and the manufacturer could face disruption. Disruption scenarios for both integrated/decentralized systems are displayed in Table 4.

3.2.1. Integrated system in the presence of disruption

In this section, the integrated system described in Section 3.1.2 is considered. The manufacturer and the supplier decide on $\overline{P}_1^{Ij}$, $\overline{P}_2^{Ij}$, $\overline{\theta}^{Ij}$, and $\overline{\varphi}^{Ij}$ for two disruption scenarios; Extra Production and Surplus Inventory.

TABLE 4. Disruption Scenarios.

Systems	Disruption kinds	Types		
		1	2	3
		Manufacturer	Supplier	Concurrent manufacturer and supplier
Integrated	Extra Production	Scenario 1		
	Surplus Inventory	Scenario 2		
Decentralized	Extra Production	Scenario 3	Scenario 4	Scenario 5
	Surplus Inventory	Scenario 6	Scenario 7	Scenario 8

Lemma 3.4 represents the change of the market potential in the two mentioned scenarios, which is similar to Rahmani and Yavari [32] as follows:

Lemma 3.4. *For the integrated model in the presence of disruption,* $\Delta a_i^{\mathrm{IE}} > 0$ *means* $\overline{D}^{\mathrm{IE}} \geq Q_I^*$, *and* $\Delta a_i^{\mathrm{IS}} < 0$ *means* $Q_I^* \geq \overline{D}^{\mathrm{IS}}$. *Moreover,* Q_I^* *is calculated from Section 3.1.2 as equation (14).*

$$Q_I^* = \left(T_{11} + \beta_2^2\left(\gamma_1^2 h + \tau\left(\lambda_1^2 - 2h(\beta_1+\rho_1)\right)\right)(C_2 + A_2)\right)/T_8. \tag{14}$$

For Scenario 1, which relates to the integrated model and the Extra Production scenario, the profit function $(\overline{\Pi}^{\mathrm{IE}}(\overline{P}_1^{\mathrm{IE}}, \overline{P}_2^{\mathrm{IE}}, \overline{\theta}^{\mathrm{IE}}, \overline{\varphi}^{\mathrm{IE}}))$ *is shown in equation (15).*

$$\begin{aligned}&\overline{\Pi}^{\mathrm{IE}}\left(\overline{P}_1^{\mathrm{IE}}, \overline{P}_2^{\mathrm{IE}}, \overline{\theta}^{\mathrm{IE}}, \overline{\varphi}^{\mathrm{IE}}\right)\\ &= \mathrm{Max}\left(\sum_{i=1}^{2}\left(\overline{P}_i^{\mathrm{IE}} - \overline{C}_i^{\mathrm{IE}}\right)\overline{D}_i^{\mathrm{IE}} - \sum_{i=1}^{2} A_i \overline{D}_i^{\mathrm{IE}} - \tau\frac{\left(\overline{\theta}^{\mathrm{IE}}\right)^2}{2} - h\frac{\left(\overline{\varphi}^{\mathrm{IE}}\right)^2}{2} - E_m^I\left(\overline{D}^{\mathrm{IE}} - Q_I^*\right)\right).\end{aligned} \tag{15}$$

In equation (15), all clauses are similar to those in equation (9). The last clause represents the cost related to Extra Production when the SC faces an Extra Production type of disruption.

Theorem 3.5. *The integrated profit function of the SC, considering disruption in the form of the Extra Production* $(\overline{\Pi}^{\mathrm{IE}}(\overline{P}_1^{\mathrm{IE}}, \overline{P}_2^{\mathrm{IE}}, \overline{\theta}^{\mathrm{IE}}, \overline{\varphi}^{\mathrm{IE}}))$, *is concave.*

Proof. Hessian matrix (H) is as follows.

$$H\left(\overline{P}_1, \overline{P}_2, \overline{\theta}, \overline{\varnothing}\right) = \begin{bmatrix} \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial\left(\overline{P}_1^{\mathrm{IE}}\right)^2} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{P}_1^{\mathrm{IE}} \partial \overline{P}_2^{\mathrm{IE}}} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{P}_1^{\mathrm{IE}} \partial \theta^{\mathrm{IE}}} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{P}_1^{\mathrm{IE}} \partial \varnothing^{\mathrm{IE}}} \\ \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{P}_2^{\mathrm{IE}} \partial \overline{P}_1^{\mathrm{IE}}} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial\left(\overline{P}_2^{\mathrm{IE}}\right)^2} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{P}_2^{\mathrm{IE}} \partial \theta^{\mathrm{IE}}} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{P}_2^{\mathrm{IE}} \partial \varnothing^{\mathrm{IE}}} \\ \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{\theta}^{rj} \partial \overline{P}_1^{\mathrm{IE}}} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{\theta}^{rj} \partial \overline{P}_2^{\mathrm{IE}}} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial\left(\overline{\theta}^{\mathrm{IE}}\right)^2} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{\theta}^{\mathrm{IE}} \partial \overline{\varnothing}^{\mathrm{IE}}} \\ \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{\varnothing}^{\mathrm{IE}} \partial \overline{P}_1^{\mathrm{IE}}} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{\varnothing}^{\mathrm{IE}} \partial \overline{P}_2^{\mathrm{IE}}} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial \overline{\varnothing}^{\mathrm{IE}} \partial \theta^{\mathrm{IE}}} & \frac{\partial^2 \overline{\Pi}^{\mathrm{IE}}}{\partial\left(\overline{\varnothing}^{\mathrm{IE}}\right)^2} \end{bmatrix}$$

$$= \begin{bmatrix} -2(\beta_1+\rho_1) & \rho_1+\rho_2 & \gamma_1 & \lambda_1 \\ \rho_1+\rho_2 & -2(\beta_2+\rho_2) & -\gamma_2 & -\lambda_2 \\ \gamma_1 & -\gamma_2 & -k & 0 \\ \lambda_1 & -\lambda_2 & 0 & -h \end{bmatrix}.$$

The proof is similar to the proof of Theorem 3.3. □

Based on Theorem 3.5, the optimum values of decision variables are obtained by equations (16)–(19).

$$\overline{P}_1^{\mathrm{IE}} = (T_{12} + (\gamma_1\gamma_2 h + \tau T_{13})T_{14})/(-h\tau T_8) \tag{16}$$

$$\overline{P}_2^{\mathrm{IE}} = \big(T_7 + T_{15} + \Delta a_1^{\mathrm{IE}}(-\tau T_{13} - \gamma_1\gamma_2 h) - \tau\Delta a_2^{\mathrm{IE}}\big(T_{16} + \gamma_1^2 h\big)\big)/T_8 \tag{17}$$

$$\begin{aligned}\overline{\theta}^{\mathrm{IE}} &= \big(E_m^I\big(\beta_1\big(\gamma_1\big(\lambda_2^2 - 2h\rho_2\big) - \gamma_2 T_{13} - 2\beta_2 h T_{17} + \beta_2(\gamma_1 T_{13}) + \gamma_2\big(2h\rho_1 - \lambda_1^2\big)\big)\big)\\ &\quad + T_9 + \Delta a_1^{\mathrm{IE}}\big(\gamma_1\big(2hT_{18} - \lambda_2^2\big) + \gamma_2 T_{13}\big) + \Delta a_2^{\mathrm{IE}}(\gamma_2 T_{16} - \gamma_1 T_{13})\big)/T_8\end{aligned} \tag{18}$$

$$\overline{\varphi}^{\mathrm{IE}} = \big(T_{10} + T_{19} - \Delta a_2^{\mathrm{IE}}(\lambda_1 T_3 + \lambda_2 T_{20}) + E_m^I\big(\beta_1\lambda_1\big(\gamma_2^2 - 2\tau\rho_2\big) - \beta_1\lambda_2 T_3\big)\big)/T_8. \tag{19}$$

For Scenario 2 corresponds to the Surplus Inventory disruption scenario, the total profit function is as shown in equation (20).

$$\begin{aligned}&\overline{\Pi}^{\mathrm{IS}}\left(\overline{P}_1^{\mathrm{IS}}, \overline{P}_2^{\mathrm{IS}}, \overline{\theta}^{\mathrm{IS}}, \overline{\varphi}^{\mathrm{IS}}\right)\\ &= \mathrm{Max}\left(\sum_{i=1}^{2}\left(\overline{P}_i^{\mathrm{IS}} - \overline{C}_i^{\mathrm{IS}}\right)\overline{D}_i^{\mathrm{IS}} - \sum_{i=1}^{2} A_i\overline{D}_i^{\mathrm{IS}} - \tau\frac{\left(\overline{\theta}^{\mathrm{IS}}\right)^2}{2} - h\frac{\left(\overline{\varphi}^{\mathrm{IS}}\right)^2}{2} - S_m^I\left(Q_I^* - \overline{D}^{\mathrm{IS}}\right)\right).\end{aligned} \tag{20}$$

The descriptions of the first four clauses are similar to those of equation (15). The last clause illustrates the cost of Surplus Inventory disruption.

Theorem 3.6. *The integrated profit function of the SC considering disruption in the form of Surplus Inventory* ($\overline{\Pi}^{\mathrm{IS}}(\overline{P}_1^{\mathrm{IS}}, \overline{P}_2^{\mathrm{IS}}, \overline{\theta}^{\mathrm{IS}}$, *and* $\overline{\varphi}^{\mathrm{IS}}$)) *is concave.*

Proof. Hessian matrix (H) is similar to the proof of Theorem 3.5. The proof is similar to that of Theorem 3.3. □

Based on Theorem 3.6, the optimum values of decision variables are obtained by equations (21)–(24).

$$\begin{aligned}\overline{P}_1^{\mathrm{IS}} &= \Big(\Big(\Delta a_1^{\mathrm{IS}} h\tau + hS_m^I(\tau(\rho_2 - T_{21}) + \gamma_1(\rho_2 - T_{21})) + \tau\lambda_1 S_m^I T_{22}\Big)\\ &\quad \times\big(\gamma_2^2 h + \tau\big(\lambda_2^2 - 2hT_{18}\big)\big) + T_{12} + T_{23}\Big)/T_8\end{aligned} \tag{21}$$

$$\overline{P}_2^{\mathrm{IS}} = \big(T_7 + T_{24} - \Delta a_2^{\mathrm{IS}}\big(\gamma_1^2 h + \tau T_{16}\big) - \Delta a_1^{\mathrm{IS}}(\tau T_{13} + \gamma_1\gamma_2 h)\big)/T_8 \tag{22}$$

$$\overline{\theta}_2^{\mathrm{IS}} = \big(T_9 + T_{25} + \beta_2 S_m^I\big(\gamma_2\big(\lambda_1^2 - 2h\rho_1\big) - \gamma_1 T_{13}\big) + \Delta a_2^{\mathrm{IS}}\big(\gamma_2\big(\lambda_1^2 - 2h\rho_1\big) - \gamma_1 T_{13}\big)\big)/T_8 \tag{23}$$

$$\overline{\varphi}_2^{\mathrm{IS}} = \big(T_{10} + T_{26} + \Delta a_2^{\mathrm{IS}}\big(\lambda_2\big(\gamma_1^2 - 2k\tau T_{21}\big) - \lambda_1(\gamma_1\gamma_2 + \tau T_{27})\big)\big)/T_8. \tag{24}$$

3.2.2. Decentralized system in the presence of disruption

In this section, the decentralized system of a manufacturer and a supplier in which the manufacturer decides on selling prices ($\overline{P}_1^{Dj}$, $\overline{P}_2^{Dj}$) and greening level ($\overline{\theta}^{Dj}$), while the supplier determines the greening level of parts ($\overline{\varphi}^{Dj}$) in the presence of three disruption types.

Lemma 3.7. *For the decentralized model, in the presence of disruption,* $\Delta a_i^{\mathrm{DE}} > 0$ *means* $\overline{D}^{\mathrm{DE}} \geq Q_D^*$, *and* $\Delta a_i^{\mathrm{DS}} < 0$ *means* $Q_D^* \geq \overline{D}^{\mathrm{DS}}$. *Moreover,* Q_D^* *is calculated as equation* (25) *(see Sect. 3.1.2).*

$$Q_D^* = \big(T_{28} - a_2 h\big(-\beta_2\gamma_1^2 - \beta_1\gamma_1\gamma_2 + 2\beta_2\tau(\beta_1 + \rho_1) + \beta_1 k(\rho_1 + \rho_2)\big)\big)/(-hT_1). \tag{25}$$

Scenario 3 of Table 3 corresponds to a decentralized model in the presence of disruption affecting the manufacturer and leading to a disruption of type Extra Production ($\Delta a_i^{\mathrm{DE}} > 0$)*. The profit function of the manufacturer*

($\overline{\Pi}_m^{\mathrm{DE}}(\overline{P}_1^{\mathrm{DE}}, \overline{P}_2^{\mathrm{DE}}, \overline{\text{and } \theta}^{\mathrm{DE}})$) is illustrated in equation (26).

$$\overline{\Pi}_m^{\mathrm{DE}}\left(\overline{P}_1^{\mathrm{DE}}, \overline{P}_2^{\mathrm{DE}}, \overline{\theta}^{\mathrm{DE}}\right) = \mathrm{Max}\left(\sum_{i=1}^{2}\left(\overline{P}_i^{\mathrm{DE}} - \overline{W}_i^{\mathrm{DE}}\right)\overline{D}_i^{\mathrm{DE}} - \sum_{i=1}^{2} A_i \overline{D}_i^{\mathrm{DE}} - \tau\frac{\left(\overline{\theta}^{\mathrm{DE}}\right)^2}{2} - E_m^D\left(\overline{D}^{\mathrm{DE}} - Q_D^*\right)\right). \quad (26)$$

Scenario 4 represents a situation in which only the disruption affects the supplier. The profit function of the supplier considering disruption in the form of Extra Production $\left(\overline{\Pi}_s^{\mathrm{DE}}(\overline{\varphi}^{\mathrm{DE}})\right)$ is shown in equation (27).

$$\overline{\Pi}_s^{\mathrm{DE}}(\overline{\varphi}^{\mathrm{DE}}) = \mathrm{Max}\left(\sum_{i=1}^{2}\left(\overline{W}_i^{\mathrm{DE}} - \overline{C}_i^{\mathrm{DE}}\right)\overline{D}_i^{\mathrm{DE}} - h\frac{\left(\overline{\varphi}^{\mathrm{DE}}\right)^2}{2} - E_s^D\left(\overline{D}^{\mathrm{DE}} - Q_D^*\right)\right). \quad (27)$$

Theorem 3.8. *The profit functions of the manufacturer and the profit function of the supplier for Scenarios 3 and 4 are concave.*

Proof. Hessian matrix (H) is similar to the proof of Theorem 3.1, and also the proof is similar to that of Theorem 3.1. □

Based on Theorem 3.8, the optimum values of decision variables for Scenario 3 are obtained by equations (28)–(31).

$$\overline{P}_{1m}^{\mathrm{DE}} = \left(T_{29} + T_{30} + \tau E_m^D\left(2\gamma_1\gamma_2 T_{27} - \gamma_2^2(2\rho_1 + \beta_1) + 2\rho_2\left(\beta_1\tau - \gamma_1^2\right) - kT_{31}{}^2\right)\right)/(-\tau T_1) \quad (28)$$

$$\begin{aligned}\overline{P}_{2m}^{\mathrm{DE}} = {} & \Big(T_{32} + E_m^D\big(k\gamma_1\gamma_2(\beta_1 + \tau T_{27}) - 2\tau\gamma_2^2 T_{21} - \tau\gamma_1^2(\beta_2 + 2\rho_2) - \Delta a_1^{\mathrm{DE}}\gamma_1\gamma_2\tau \\ & + \tau^2\Delta a_1^{\mathrm{DE}} T_{27} + \tau^2\left(2\beta_2 T_{21} - T_{31}{}^2 + \beta_1(3\rho_2 - \rho_1)\right)\big) + \tau\Delta a_2^{\mathrm{DE}}\left(2\tau T_{21} - \gamma_1^2\right)\Big)/(-\tau T_1) \quad (29)\end{aligned}$$

$$\overline{\theta}_m^{\mathrm{DE}} = \left(T_{33} + T_{34} - 2\beta_1\tau E_m^{\mathrm{DE}} T_{17} - \gamma_1(W_1 + A_1) + 2\tau\beta_1(\gamma_1(W_1 + A_1) - \gamma_2 W_2)\right)/(-\tau T_1) \quad (30)$$

$$\overline{\varphi}_m^{\mathrm{DE}} = \frac{-C_1\lambda_1 + C_2\lambda_2 + \lambda_1 W_1 - \lambda_2 W_2}{\tau}. \quad (31)$$

Similarly, equations (32)–(35) give closed forms of optimal values of decision variables for Scenario 4.

$$\overline{P}_{1s}^{\mathrm{DE}} = \left(T_{35} + \left(\gamma_2^2 - 2\tau T_{18}\right)\left(\tau\Delta a_1^{\mathrm{DE}} - \lambda_1 E_s^D T_{22}\right) + T_3\left(\tau\Delta a_2^{\mathrm{DE}} + \lambda_2 E_s^D T_{22}\right)\right)/\tau T_1 \quad (32)$$

$$\begin{aligned}\overline{P}_{2s}^{\mathrm{DE}} = {} & \left(T_{32} + E_s^D\left(\lambda_1^2 T_3 + \lambda_1\lambda_2(\tau(2\beta_1 + 3\rho_1 + \rho_2) - \gamma_1(\gamma_1 + \gamma_2)) + \lambda_2^2\left(\gamma_1^2 - 2\tau T_{21}\right)\right)\right. \\ & \left. - \tau\Delta a_1^{\mathrm{DE}} T_3 + \tau\Delta a_2^{\mathrm{DE}}\left(2\tau T_{21} - \gamma_1^2\right)\right)/(-\tau T_1) \quad (33)\end{aligned}$$

$$\overline{\theta}_s^{\mathrm{DE}} = \left(T_{33} + T_{36} + E_s^D\left(\lambda_1^2(\gamma_2 T_{27} - 2\gamma_1 T_{18}) + \lambda_2^2(2\gamma_2 T_{21} - \gamma_1 T_{27})\right)\right)/(-\tau T_1) \quad (34)$$

$$\overline{\varphi}_s^{\mathrm{DE}} = \frac{C_2\lambda_2 - C_1\lambda_1 + E_s^D(\lambda_2 - \lambda_1) + \lambda_1 W_1 - \lambda_2 W_2}{\tau}. \quad (35)$$

Scenario 5 represents a situation in which the disruption affects both the manufacturer and the supplier in the Extra Production form. The profit function of the manufacturer ($\overline{\Pi}_c^{\mathrm{DE}}(\overline{P}_1^{\mathrm{DE}}, \overline{P}_2^{\mathrm{DE}}, \overline{\theta}^{\mathrm{DE}})$) and the profit function of the supplier $\overline{\Pi}_c^{\mathrm{DE}}(\overline{\varphi}^{\mathrm{DE}})$ are similar to those of Scenarios 3 and 4, respectively. Equations (36)–(39) give closed forms of optimal values of decision variables for this scenario.

$$\overline{P}_{1c}^{\mathrm{DE}} = \left(E_c^d\left(\gamma_2\left(\lambda_1^2 + \gamma_1\left(\lambda_2^2 - \lambda_1\lambda_2 + 2\tau T_{27}\right)\right) + 2\tau\left(\rho_2\left(\beta_1 - \lambda_1^2 - \gamma_1^2\right) - \gamma_2^2 T_{21}\right)\right) + T_{29} + T_{37}\right)/(-kT_1) \quad (36)$$

$$\overline{P}_{2c}^{\mathrm{DE}} = \left(T_{32} + T_{38} - \tau A_2\left(2\beta_2\tau T_{21} + \left(2\gamma_1\gamma_2 - \gamma_1^2 + \tau(2\beta_1 + \rho_1)\right)\rho_2 - \tau\rho_2^2\right) - \beta_2\gamma_1^2\right)/(-\tau T_1) \quad (37)$$

$$\overline{\theta}_c^{\mathrm{DE}} = \Big(T_{39} + T_{40} + \tau\Delta a_2^{de}(\gamma_1 T_{27} - 2\beta_1\gamma_2) + \tau\Delta a_1^{de}(2\gamma_1(\rho_2 + \beta_2\tau) - \gamma_2 T_{27})\Big)/(-kT_1) \quad (38)$$

$$\overline{\varphi}_c^{\mathrm{DE}} = \frac{C_2\lambda_2 - C_1\lambda_1 + E_c^D(\lambda_2-\lambda_1) + \lambda_1 W_1 - \lambda_2 W_2}{\tau}. \tag{39}$$

Scenario 6 is similar to Scenario 3; however,in the presence of Surplus Inventory disruption. The profit function of the manufacturer considering disruption in the form of Surplus Inventory is shown in equation (40).

$$\overline{\Pi}_m^{\mathrm{DS}}\left(\overline{P}_1^{\mathrm{DS}}, \overline{P}_2^{\mathrm{DS}}, \overline{\theta}^{\mathrm{DS}}\right) = \mathrm{Max}\left(\sum_{i=1}^{2}\left(\overline{P}_i^{\mathrm{DS}} - \overline{W}_i^{\mathrm{DS}}\right)\overline{D}_i^{\mathrm{DS}} - \sum_{i=1}^{2} A_i \overline{D}_i^{\mathrm{DS}} - \tau\frac{\left(\overline{\theta}^{\mathrm{DS}}\right)^2}{2} - S_m^D\left(Q_D^* - \overline{D}^{\mathrm{DS}}\right)\right). \tag{40}$$

For Scenario 7, the profit function of the supplier in the decentralized system considering Surplus Inventory disruption is shown in equation (41).

$$\overline{\Pi}_s^{\mathrm{DS}}\left(\overline{\varphi}^{\mathrm{DS}}\right) = \mathrm{Max}\left(\sum_{i=1}^{2}\left(\overline{W}_i^{\mathrm{DS}} - \overline{C}_i^{\mathrm{DS}}\right)\overline{D}_i^{\mathrm{DS}} - h\frac{\left(\overline{\varphi}^{\mathrm{DS}}\right)^2}{2} - S_s^D\left(Q_D^* - \overline{D}^{\mathrm{DS}}\right)\right). \tag{41}$$

Theorem 3.9. *The profit functions of the manufacturer and the supplier for Scenarios 6 and 7 are concave.*

Proof. Hessian matrix (H) is similar to the proof of Theorem 3.1, and also the proof is similar to that of Theorem 3.1. □

Based on Theorem 3.9, the optimum values of decision variables for Scenario 6 are obtained by equations (42)–(45).

$$\overline{P}_{1m}^{\mathrm{DS}} = \left(T_{35} + T_3\left(\tau\Delta a_2^{\mathrm{DS}} + S_m^D\left(\gamma_2^2 - T_3 - \tau\beta_2\right)\right) + \left(\gamma_2^2 - 2\tau T_{18}\right)\left(\tau\Delta a_1^{\mathrm{DS}} + S_m^D\left(\gamma_1^2 - T_3 - \tau\beta_1\right)\right)/\tau T_1 \tag{42}$$

$$\begin{aligned}\overline{P}_{2m}^{\mathrm{DS}} = &\Big(\tau S_m^D\Big(\tau\big(\rho_1(\beta_1 - 2\beta_2) + {T_{31}}^2 - \beta_1(3\rho_2 + 2\beta_2)\big) + \gamma_1^2(\beta_2 + 2\rho_2) + 2\gamma_2^2 T_{21} - \gamma_1\gamma_2(2T_{27} - \beta_1)\Big)\\ &+ \tau\Delta a_2^{\mathrm{DS}}\left(2kT_{21} - \gamma_1^2\right)T_{32} - \tau^2\Delta {a_1}^{\mathrm{DS}} T_3\Big)/(-\tau T_1)\end{aligned} \tag{43}$$

$$\begin{aligned}\overline{\theta}_m^{\mathrm{DS}} = &\left(T_{33} + \tau S_m^D(\beta_1(2\gamma_1\rho_2 - \gamma_2 T_{27}) + \beta_2(2\beta_1 T_{17} + \rho_1 T_{17} + \gamma_1\rho_2))\right.\\ &\left.+ \tau\left(\Delta a_1^{\mathrm{DS}}(2\gamma_1 T_{18} - \gamma_2 T_{27}) + \Delta a_2^{\mathrm{DS}}(\gamma_1 T_{27} - 2\gamma_2 T_{21})\right)\right)/(-\tau T_1)\end{aligned} \tag{44}$$

$$\overline{\varphi}_m^{\mathrm{DS}} = \frac{C_2\lambda_2 - C_1\lambda_1 + \lambda_1 W_1 - \lambda_2 W_2}{\tau}. \tag{45}$$

Based on Theorem 3.9, the optimum values of decision variables for Scenario 7 are obtained by equations (46)–(49).

$$\overline{P}_{1s}^{\mathrm{DS}} = \left(T_{35} + \left(\gamma_2^2 - 2\tau T_{18}\right)\left(\Delta {a_1}^{\mathrm{DS}}\tau + \lambda_1 S_s^D T_{22}\right) + T_3\left(\Delta a_2^{\mathrm{DS}}\tau - \lambda_2 S_s^D T_{22}\right)\right)/\tau T_1 \tag{46}$$

$$\begin{aligned}\overline{P}_{2s}^{\mathrm{DS}} = &\left(T_{32} + S_s^D\left(\lambda_1\lambda_2\left(\gamma_1^2 + \gamma_1\gamma_2 - \tau(2\beta_1 + \rho_2 + 3\rho_1)\right) + \lambda_2^2\left(2\beta_1\tau - \gamma_1^2\right) - \lambda_1^2 T_3\right) - \tau\Delta {a_1}^{\mathrm{DS}} T_3\right.\\ &\left.+ \tau\Delta a_2^{\mathrm{DS}}\left(2\tau T_{21} + \gamma_1^2\right)\right)/(-\tau T_1)\end{aligned} \tag{47}$$

$$\overline{\theta}_s^{\mathrm{DS}} = \left(T_{33} + T_{41} + \tau\Delta a_2^{\mathrm{DS}}(\gamma_1 T_{27} - 2\gamma_2 T_{21}) + \tau(T_{31}\rho_2(2\beta_1\gamma_2 + \gamma_1) - \gamma_2\rho_1 T_{31})A_2\right)/(-\tau T_1) \tag{48}$$

$$\overline{\varphi}_s^{\mathrm{DS}} = \frac{C_2\lambda_2 - C_1\lambda_1 + \lambda_1(S_s^D + W_1) - \lambda_2(S_s^D + W_2)}{\tau}. \tag{49}$$

Similar to what we have in Scenario 5, the disruption affects the manufacturer and the supplier in Scenario 8, although the effect is in the form of Surplus Inventory. The profit functions for the manufacturer and the supplier $(\overline{\Pi}_c^{\mathrm{DS}}(\overline{P}_1^{\mathrm{DS}}, \overline{P}_2^{\mathrm{DS}}, \overline{\theta}^{\mathrm{DS}}), \overline{\Pi}_c^{\mathrm{DS}}(\overline{\varphi}^{\mathrm{DS}})$ are similar to those of Scenarios 6 and 7, respectively. Equations (50)–(53) give closed forms of optimal values of decision variables for Scenario 8.

$$\overline{P}_{1c}^{\mathrm{DS}} = \left(T_{29} + T_{42} + \tau\left(\beta_2(2a_1\tau + \gamma_2(W_2 + A_2)) + 2\Delta {a_1}^{\mathrm{DS}}\left(\tau T_{18} - \gamma_2^2\right) - \Delta {a_2}^{\mathrm{DS}} T_3\right)\right)/(-\tau T_1) \tag{50}$$

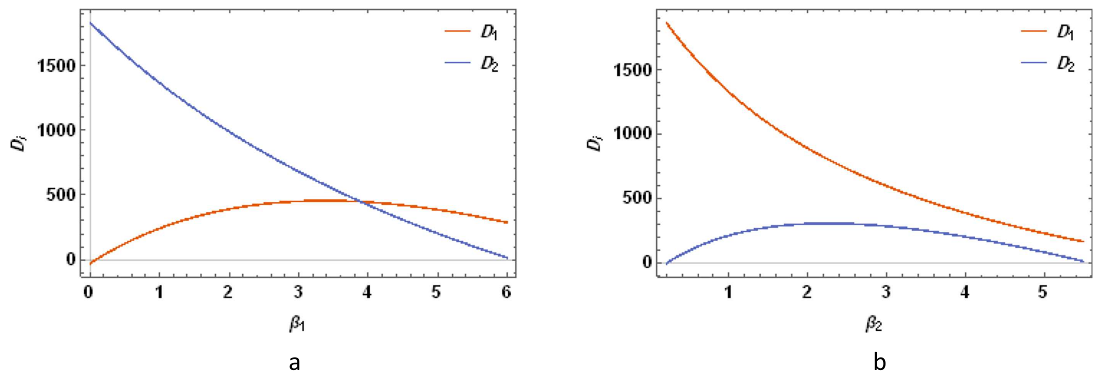

FIGURE 2. Demands *versus* price sensitivity coefficient for products. (a) Demand *versus* β_1 in Scenario 5. (a) Demand *versus* β_2 in Scenario 5.

$$\overline{P}_{2c}^{\mathrm{DS}} = \big(\tau\big(\gamma_2(\gamma_1\rho_1 - 2\gamma_2 T_{21}) - \tau\rho_2^2 + (\gamma_1(2\gamma_2 - \gamma_1) + \tau A_2(2\beta_1 + \rho_1))\rho_2\big)\big(S_c^D - W_2 - A_2\big)(T_{32} + T_{43})\big)/(-\tau T_1) \tag{51}$$

$$\overline{\theta}_c^{\mathrm{DS}} = \big(T_{39} + T_{44} + \tau\big(\Delta a_2^{\mathrm{DS}}(\gamma_1 T_{27} - 2\gamma_2 T_{21}) + \Delta a_1^{\mathrm{DS}}(2\gamma_1 T_{18} - \gamma_2 T_{27})\big)\big)/(-\tau T_1) \tag{52}$$

$$\overline{\varphi}_c^{\mathrm{DS}} = \frac{S_c^D(\lambda_1 - \lambda_2) - C_1\lambda_1 + C_2\lambda_2 + \lambda_1 W_1 - \lambda_2 W_2}{\tau}. \tag{53}$$

The effect of changes in the price sensitivity coefficient of product types (β_i) on demand for both green and non-green products for Scenario 5 is represented in Figure 2. In Figure 2a, increasing β_1 by 3.7 increases the demand for the green product (D_1), and for β_1 greater than 3.7, the demand (D_2) decreases. Moreover, Figure 2b shows that β_2 has a negative effect on D_1, while it increases D_2 for $\beta_2 \leq 2.3$. For Scenario 8, similar behavior is observed.

4. Government intervention in the decentralized system considering the disruption

Developing green products have extra development costs for the manufacturer, so the government intervenes to encourage the manufacturer to develop green product. GI is exerted through subsidy-taxation policy. The government subsidizes the manufacturer to make developing the green product profitable. On the other hand, the government receives some portion of the manufacturer's income as tax to increase both the economic and the social utilities. The government plays the role of leader, whereas the manufacturer acts as a follower. Moreover, the manufacturer plays the role of a leader for the supplier. Here, Scenarios 5 and 8, displayed in Table 3, are investigated in the presence of GI.

Similar to what we have in Section 3, the manufacturer decides on P_1, P_2, and θ, while the supplier only decides on φ. Furthermore, the government decides on the intervention rate (δ). The government contribution in costs and revenues is δ and $(1-\delta)$, respectively. For Scenarios 5 and 8 in Table 3 (depending on the definition for each scenario), the profit functions of the supplier, manufacturer, and government are as follows. The detailed table of two scenarios for GI in green products is in Appendix B.

In the case of Extra Production disruption, the profit function of the supplier ($\overline{\Pi}_s^{\mathrm{DE}^*}$) is as equation (27), while in the case of Surplus Inventory, its profit function ($\overline{\Pi}_s^{\mathrm{DS}^*}$) is as equation (41). In the case of Extra Production disruption, the profit function of the manufacturer ($\overline{\Pi}_m^{\mathrm{DE}^*}$) is as equation (54).

$$\overline{\Pi}_m^{\mathrm{DE}^*}\left(\overline{P}_1^{\mathrm{DE}^*},\overline{P}_2^{\mathrm{DE}^*},\overline{\theta}^{\mathrm{DE}^*}\right)=\mathrm{Max}\Bigg(\left(\delta\overline{P}_1^{\mathrm{DE}^*}-(1-\delta)\overline{W}_1^{\mathrm{DE}}\right)\overline{D}_1^{\mathrm{DE}}+\left(\overline{P}_2^{\mathrm{DE}^*}-\overline{W}_2^{\mathrm{DE}}\right)\overline{D}_2^{\mathrm{DE}}$$
$$-\sum_{i=1}^{2}A_i\overline{D}_i^{\mathrm{DE}}-(1-\delta)\tau\frac{\left(\overline{\theta}^{\mathrm{DE}^*}\right)^2}{2}-E_c^D\left(\overline{D}^{\mathrm{DE}}-Q_D^*\right)\Bigg). \tag{54}$$

In equation (54), the first clause indicates the portion of income and costs that the manufacturer should bear for the green products according to the income tax paid to the government and the subsidy received from the government for green products. The second clause is the manufacturer's revenue from the non-green product, and the third one is the administrative cost of the manufacturer. Moreover, the fourth is the portion of costs for the greening efforts that the manufacturer should bear. The last clause represents the Extra Production of the manufacturer when the SC faces disruption.

Theorem 4.1. *The decentralized profit function of the manufacturer in the presence of Extra Production disruption* ($\overline{\Pi}_m^{\mathrm{DE}^*}(\overline{P}_1^{\mathrm{DE}^*}, \overline{P}_2^{\mathrm{DE}^*}, \overline{\theta}^{\mathrm{DE}^*})$) *is concave in* $\overline{P}_1^{\mathrm{DE}^*}$, $\overline{P}_2^{\mathrm{DE}^*}$, *and* $\overline{\theta}^{\mathrm{DE}^*}$, *if* $\frac{\gamma_1}{2\gamma_2}>\frac{\beta_1+\rho_1}{\rho_1\delta+\rho_2}$ *and* $\frac{2\delta\gamma_1}{\gamma_2}<\frac{\rho_1\delta+\rho_2}{\rho_2+\beta_2}$.

Proof. Hessian matrix (H) is as follows.

$$H\left(\overline{P}_1^{\mathrm{DE}^*},\overline{P}_2^{\mathrm{DE}^*},\overline{\theta}^{\mathrm{DE}^*}\right)=\begin{bmatrix}\frac{\partial^2\overline{\Pi}_m^{\mathrm{DE}^*}}{\partial\,\overline{P}_1^{\mathrm{DE}^*2}} & \frac{\partial^2\overline{\Pi}_m^{\mathrm{DE}^*}}{\partial\overline{P}_1^{\mathrm{DE}^*}\partial\,\overline{P}_2^{\mathrm{DE}^*}} & \frac{\partial^2\overline{\Pi}_m^{\mathrm{DE}^*}}{\partial\overline{P}_1^{\mathrm{DE}^*}\partial\overline{\theta}^{\mathrm{DE}^*}}\\ \frac{\partial^2\overline{\Pi}_m^{\mathrm{DE}^*}}{\partial P_2\partial\overline{P}_1^{\mathrm{DE}^*}} & \frac{\partial^2\overline{\Pi}_m^{\mathrm{DE}^*}}{\partial\,\overline{P}_2^{\mathrm{DE}^*2}} & \frac{\partial^2\overline{\Pi}_m^{\mathrm{DE}^*}}{\partial\,\overline{P}_2^{\mathrm{DE}^*}\partial\overline{\theta}^{\mathrm{DE}^*}}\\ \frac{\partial^2\overline{\Pi}_m^{\mathrm{DE}^*}}{\partial\overline{\theta}^{\mathrm{DE}^*}\partial\overline{P}_1^{\mathrm{DE}^*}} & \frac{\partial^2\overline{\Pi}_m^{\mathrm{DE}^*}}{\partial\overline{\theta}^{\mathrm{DE}^*}\partial\,\overline{P}_2^{\mathrm{DE}^*}} & \frac{\partial^2\overline{\Pi}_m^{\mathrm{DE}^*}}{\partial\overline{\theta}^{\mathrm{DE}^*2}}\end{bmatrix}$$
$$=\begin{bmatrix}-2\delta(\beta_1+\rho_1) & \rho_1\delta+\rho_2 & \gamma_1\delta\\ \rho_1\delta+\rho_2 & -2(\beta_2+\rho_2) & -\gamma_2\\ \gamma_1\delta & -\gamma_2 & -k(1-\delta)\end{bmatrix}.$$

The first principal minor determinant of profit function ($\overline{\Pi}_m^{de^*}$) is $(-2\delta(\beta_1+\rho_1))<0$. Besides, the second principal minor determinant of profit function is positive $(2\delta\rho_2(2\beta_1+\rho_1)+\delta(4\beta_1\beta_2+\rho_1(4\beta_2-\rho_1\delta))-\rho_2^2)>0$ and the third principal minor determinant is negative $(-k(1-\delta)(4\delta(\beta_1+\rho_1)(\beta_2+\rho_2)-(\rho_1\delta+\rho_2)^2)-\delta\gamma_2(-2\beta_1\gamma_2+\rho_1\delta\gamma_1-2\rho_1\gamma_2+\rho_2\gamma_1)+\delta\gamma_1(-\rho_1\delta\gamma_2+2\rho_2\delta\gamma_1-\rho_2\gamma_2+2\beta_2\delta\gamma_1))<0$ due to the model assumption. Hence, The Hessian matrix of the profit function is negative semidefinite if the assumptions hold. □

Based on Theorem 4.1, a closed form for the optimum decision variables can be obtained by equations (55)–(58).

$$\overline{P}_1^{\mathrm{DE}^*}=k(1-\delta)\big(T_{45}+\gamma_1\delta\big(E_c^D(\gamma_2-\gamma_1)+\gamma_1((\delta-1)W_1-A_1)+\gamma_2(W_2+A_2)\big)\big)/T_{46} \tag{55}$$
$$\overline{P}_2^{\mathrm{DE}^*}=\Big(T_{48}+T_{49}+\tau\delta\Delta a_1^{\mathrm{DE}}(\gamma_1\gamma_2\delta-\tau\rho_2-\tau\delta(\rho_1+\rho_2+\rho_1\delta))\Big)/\ (-T_{47}) \tag{56}$$
$$\overline{\theta}^{\mathrm{DE}^*}=\big(T_{50}+T_{51}+\Delta a_1^{\mathrm{DE}}\big(2\beta_2\gamma_1\tau\delta^2-\gamma_2\tau\rho_1\delta^2+2\gamma_1\tau\rho_2\delta^2-\gamma_2\tau\rho_2\delta\big)\big)/T_{47} \tag{57}$$
$$\overline{\varphi}^{\mathrm{DE}^*}=\frac{C_2\lambda_2-C_1\lambda_1-E_c^D\lambda_1+E_c^d\lambda_2+\lambda_1W_1-\lambda_2W_2}{\tau}. \tag{58}$$

Furthermore, in the case of the Surplus Inventory type of disruption, the profit function ($\overline{\Pi}_m^{\mathrm{DS}^*}$) is as equation (59).

$$\overline{\Pi}_m^{\mathrm{DS}^*}\left(\overline{P}_1^{\mathrm{DS}^*},\overline{P}_2^{\mathrm{DS}^*},\overline{\theta}^{\mathrm{DS}^*}\right) = \mathrm{Max}\left(\left(\delta\overline{P}_1^{\mathrm{DS}^*} - (1-\delta)\overline{W}_1^{\mathrm{DS}}\right)\overline{D}_1^{\mathrm{DS}} + \left(\overline{P}_2^{\mathrm{DS}^*} - \overline{W}_2^{\mathrm{DS}}\right)\overline{D}_2^{\mathrm{DS}} - \sum_{i=1}^{2} A_i\overline{D}_i^{\mathrm{DS}} - (1-\delta)\tau\frac{\left(\overline{\theta}^{\mathrm{DS}^*}\right)^2}{2} - S_c^D\left(Q_D^* - \overline{D}^{\mathrm{DS}}\right)\right). \tag{59}$$

Theorem 4.2. *The decentralized profit function of the manufacturer in the presence of disruption in the form of Surplus Inventory ($\overline{\Pi}_m^{\mathrm{DS}^*}(\overline{P}_1^{\mathrm{DS}^*}, \overline{P}_2^{\mathrm{DS}^*}, \overline{\theta}^{\mathrm{DS}^*})$) is concave in $\overline{P}_1^{\mathrm{DS}^*}, \overline{P}_2^{\mathrm{DS}^*}$, and $\overline{\theta}^{\mathrm{DS}^*}$.*

Proof. Hessian matrix (H) is similar to the proof of Theorem 4.1, and also the proof is similar to that of Theorem 4.1. □

Based on Theorem 4.2, a closed form for the optimum decision variables can be obtained by equations (60)–(63).

$$\overline{P}_1^{\mathrm{DS}^*} = \left(T_{52} + k(\delta-1)\left(-\tau\delta\Delta a_2^{\mathrm{DS}} - C_1\lambda_1\lambda_2\delta + C_2\lambda_2^2\delta + \tau a_2(1-\delta)\right)\right)/T_{46} \tag{60}$$

$$\overline{P}_2^{\mathrm{DS}^*} = \left(T_{48} + T_{53} + \tau\delta\Delta a_1^{\mathrm{DS}}\left(\gamma_1\gamma_2\delta - \tau\delta\rho_1 + \tau\delta\rho_2 + \tau\rho_1\delta^2 - \tau\rho_2\right)\right)/(-T_{47}) \tag{61}$$

$$\overline{\theta}^{\mathrm{DS}^*} = \left(T_{50} + T_{54} + \tau\delta\Delta a_1^{\mathrm{DS}}(2\beta_2\gamma_1\delta - \gamma_2\rho_2 - \gamma_2\rho_1\delta + 2\gamma_1\rho_2\delta)\right)/\ T_{47} \tag{62}$$

$$\overline{\varphi}^{\mathrm{DS}^*} = \frac{S_c^D\lambda_1 - C_1\lambda_1 + C_2\lambda_2 - S_c^D\lambda_2 + \lambda_1 W_1 - \lambda_2 W_2}{\tau}. \tag{63}$$

The utility function of the government considering disruption is as equation (64) for $j = E, S$.

$$\overline{\Pi}_g^{j^*}(\delta) = \zeta_1\left[\left((1-\delta)\overline{P}_1^{Dj} - \delta\overline{W}_1^{Dj}\right)\overline{D}_1^{Dj} - \delta\tau\frac{\left(\overline{\theta}^{Dj}\right)^2}{2}\right] + \zeta_2\left[S'\overline{\theta}^{Dj}\overline{D}_1^{Dj}\right]. \tag{64}$$

In equation (64), the government's economic and social utilities are considered. The first clause represents the economic utility of government, and the second indicates its social utility. Government economic utility consists of income tax and subsidy. Furthermore, the social utility of government relates to customer satisfaction.

5. Channel coordination through cost sharing contract in the presence of disruption

Due to the nature of each SC member, profits gained by members are different. Normally, some members do not join the SC for economic reasons, although to achieve the highest profit, it is necessary to coordinate the SC. To convince the SC members to act coordinately, a cost-sharing contract between the manufacturer and the supplier is beneficial. Based on the contract, the supplier would share some portion of its cost with the manufacturer, and in return, the manufacturer would benefit from the coordinated situation and gain more profit than the decentralized system. Here, the cost-sharing contract in two types of disruption is investigated.

5.1. Channel coordination in the presence of Extra Production disruption

Consider Scenario 5, in which the disruption of the type of Extra Production impacts both the manufacturer and the supplier. The total expected profit of the supplier ($\overline{\Pi}_s^{co-\mathrm{DE}}$) is shown in equation (65).

$$\overline{\Pi}_s^{co-\mathrm{DE}}\left(\overline{\varphi}^{\mathrm{DE}}\right) = \mathrm{Max}\left(\left(\overline{W}_1^{\mathrm{DE}} - \Omega\overline{C}_1^{\mathrm{DE}}\right)\overline{D}_1^{\mathrm{DE}} + \left(\overline{W}_2^{\mathrm{DE}} - \overline{C}_2^{\mathrm{DE}}\right)\overline{D}_2^{\mathrm{DE}} - h\frac{\left(\overline{\varphi}^{\mathrm{DE}}\right)^2}{2} - E_c^D\left(\overline{D}^{\mathrm{DE}} - Q_D^*\right)\right). \tag{65}$$

Furthermore, the total expected profit of the manufacturer ($\overline{\Pi}_m^{co-\mathrm{DE}}$) could be examined as equation (66).

$$\overline{\Pi}_m^{co-\mathrm{DE}}\left(\overline{P}_1^{\mathrm{DE}}, \overline{P}_2^{\mathrm{DE}}, \overline{\theta}^{\mathrm{DE}}\right) = \mathrm{Max}\left(\sum_{i=1}^{2}\left(\overline{P}_i^{\mathrm{DE}} - \overline{W}_i^{\mathrm{DE}}\right)\overline{D}_i^{\mathrm{DE}} - \sum_{i=1}^{2} A_i\overline{D}_i^{\mathrm{DE}} - \tau\frac{\left(\overline{\theta}^{\mathrm{DE}}\right)^2}{2} - E_c^D\left(\overline{D}^{\mathrm{DE}} - Q_D^*\right) - (1-\Omega)\overline{C}_1^{\mathrm{DE}}\overline{D}_1^{\mathrm{DE}}\right). \tag{66}$$

The manufacturer and the supplier participate in the contract only if their profit values increase compared to those of the decentralized model. Hence, the critical conditions should hold for implementing the contract (Eqs. (67) and (68)).

$$\overline{\Pi}_s^{co-\mathrm{DE}}\left(\overline{\varphi}^I\right) > \overline{\Pi}_s^{\mathrm{DE}}\left(\overline{\varphi}^{\mathrm{DE}}\right) \tag{67}$$

$$\overline{\Pi}_m^{co-\mathrm{DE}}\left(\overline{P}_1^I, \overline{P}_2^I, \overline{\theta}^I\right) > \overline{\Pi}_m^{\mathrm{DE}}\left(\overline{P}_1^{\mathrm{DE}}, \overline{P}_2^{\mathrm{DE}}, \overline{\theta}^{\mathrm{DE}}\right). \tag{68}$$

5.2. Channel coordination in the presence of Surplus Inventory disruption

Consider Scenario 8, in which the disruption of type Surplus Inventory impacts both the manufacturer and the supplier. The total expected profit of the supplier ($\overline{\Pi}_s^{co-\mathrm{DS}}$) and the total expected profit of the manufacturer ($\overline{\Pi}_m^{co-\mathrm{DS}}$) are given in equations (69) and (70).

$$\overline{\Pi}_s^{co-\mathrm{DS}}\left(\overline{\varphi}^{\mathrm{DS}}\right) = \mathrm{Max}\left(\left(\overline{W}_1^{\mathrm{DS}} - \Omega\overline{C}_1^{\mathrm{DS}}\right)\overline{D}_1^{\mathrm{DS}} + \left(\overline{W}_2^{\mathrm{DS}} - \overline{C}_2^{\mathrm{DS}}\right)\overline{D}_2^{\mathrm{DS}} - h\frac{\left(\overline{\varphi}^{\mathrm{DS}}\right)^2}{2} - S_c^D\left(Q_D^* - \overline{D}^{\mathrm{DS}}\right)\right) \tag{69}$$

$$\overline{\Pi}_m^{co-\mathrm{DS}}\left(\overline{P}_1^{\mathrm{DS}}, \overline{P}_2^{\mathrm{DS}}, \overline{\theta}^{\mathrm{DS}}\right) = \mathrm{Max}\left(\sum_{i=1}^{2}\left(\overline{P}_i^{\mathrm{DS}} - \overline{W}_i^{\mathrm{DS}}\right)\overline{D}_i^{\mathrm{DS}} - \sum_{i=1}^{2} A_i\overline{D}_i^{\mathrm{DS}} - \tau\frac{\left(\overline{\theta}^{\mathrm{DS}}\right)^2}{2} - S_c^D\left(Q_D^* - \overline{D}^{\mathrm{DS}}\right) - (1-\Omega)\overline{C}_1^{\mathrm{DS}}\overline{D}_1^{\mathrm{DS}}\right). \tag{70}$$

The critical condition to convince SC members to coordinate should hold (Eqs. (71) and (72)).

$$\overline{\Pi}_s^{co-\mathrm{DS}}\left(\overline{\varphi}^I\right) > \overline{\Pi}_s^{\mathrm{DS}}\left(\overline{\varphi}^{\mathrm{DS}}\right) \tag{71}$$

$$\overline{\Pi}_m^{co-\mathrm{DS}}\left(\overline{P}_1^I, \overline{P}_2^I, \overline{\theta}^I\right) > \overline{\Pi}_m^{\mathrm{DS}}\left(\overline{P}_1^{\mathrm{DS}}, \overline{P}_2^{\mathrm{DS}}, \overline{\theta}^{\mathrm{DS}}\right). \tag{72}$$

6. Case study

This section investigates some examples based on an Iranian automotive company [SaipaCorp.com]. Also, a sensitivity analysis of important parameters is implemented.

Table 5. Parameter values for the numerical experiments.

No.	β_1	β_2	ρ_1	ρ_2	γ_1	γ_2	λ_1	λ_2
1	5	4	2	1.5	600	450	6	5
2	6	4	3	2.5	1400	700	10	2
3	4	2	5	4	700	650	7	4
4	6	2	10	7	800	500	11	7
5	4	1	7	6	670	550	5	4

6.1. Numerical examples of models (without government intervention)

Here, ten numerical examples are solved to illustrate the theoretical results of the proposed ASC model. The value of wholesale prices have been achieved form the studiew in Iran automotive market [40]. In addition, the amount of government intervention on automotive supply chain has been extracted from relevant papers [19]. The following parameters are based on the information provided by the interviewed Iranian automotive experts [SaipaCorp.com]:

$$h = 3000,\ \tau = 2000,\ a_1 = 2000,\ a_2 = 4000,\ C_1 = 500,\ C_2 = 300,\ W_1 = 600,\ W_2 = 400,\ A_1 = 100,\ A_2 = 80,$$
$$\Delta a_i^{rE} = 20,\ \Delta a_i^{rS} = -20,\ E_k^r = 0.2,\ \text{and}\ S_k^r = 0.2.$$

Furthermore, the values of other parameters, which are different in five numerical examples, are given in Table 5.

When there is no disruption, the obtained value of the decision variables in Example 1 is $P_1 = 766.2$, $P_2 = 538.7$, $\theta = 4.4$, and $\varphi = 0.1$. Demands for the green and non-green products are $D_1 = 375.3$ and $D_2 = 190.4$, respectively. Furthermore, the profit values of the supplier and the manufacturer are $\Pi_s = 56575.4$ and $\Pi_m = 6520.4$, respectively. For different disruption scenarios, the obtained values of the decision variables and also the demand and the profit values are calculated in Table 6 (abbreviations WD, D, and I represent without disruption, decentralized, and integrated, respectively). The results indicated that the total profit value for the decentralized model in case of disruption (Extra Production) is higher than without disruption. *Vice versa*, the total profit value for the decentralized model in case of disruption (Surplus Inventory) is lower than without disruption.

6.2. Numerical examples of models with government intervention

In this section, five numerical examples represent the results of GI in the SC. The parameters of these examples are the same as what we have in Section 6.1. The rest of the coefficients $(\zeta_1, \zeta_2, \delta, S')$ for the five examples are equal to what is illustrated in Table 7. These values are obtained based on the information provided by Iranian Automotive experts. Furthermore, Table 8 represents the numerical results of ten examples in the presence of GI.

6.3. Numerical examples of models with Cost Sharing contract

In this section, five numerical examples represent the cost-sharing contract's results in the SC. The parameters of these examples are the same as what we have in Section 6.1. Moreover, the franchise parameter (F) is considered 100 000 for Example 1; 80 000 for Example 2; 160 000 for Examples 3 and 4; 210 000 for Example 5. Furthermore, Table 9 represents the numerical results of five examples in the presence of contract (cost-sharing) for two Scenarios (5 and 8) (abbreviations D and I represent decentralized and integrated, respectively).

7. Sensitivity analysis

Figure 3a illustrates the changes in the profit functions for the scenario without disruption (decentralized) when γ_1 changes. The chart represents that an increase in γ_1 increases the profit of both the manufacturer and

Table 6. The results of the numerical examples before/after disruption.

No.	Scenarios		P_1	P_2	θ	φ	D_1	D_2	Π_s	Π_m	Π
1	D	WD	766.2	538.7	4.4351	0.0500	375.3	190.4	56 575.4	6520.4	63 095.8
		3	768.2	541.4	4.4319	0.0333	384.5	200.3	58 477.8	9057.7	67 535.5
		4	768.1	541.3	4.4316	0.0333	384.9	200.8	58 561.8	9061.6	67 623.3
		5	768.2	541.4	4.4319	0.0333	384.5	200.3	58 474.0	9057.7	67 531.7
		6	764.2	536.0	4.4386	0.0333	366.2	180.5	54 675.8	4061.8	58 737.7
		7	764.3	536.1	4.4389	0.0334	365.8	180.1	54 583.9	4065.7	58 649.6
		8	764.2	536.0	4.4386	0.0334	366.2	180.5	54 672.0	4061.8	58 733.9
	I	WD	708.3	496.1	4.2494	0.0347	583.9	421.7	–	–	85 090.0
		1	710.3	498.7	4.2461	0.0341	593.6	431.6	–	–	89 618.0
		2	706.3	493.4	4.2527	0.0354	574.8	411.8	–	–	80 644.2
2	D	WD	754.4	578.6	2.3514	0.4000	242.6	478.0	71 904.5	52 042.2	123 946.7
		3	755.7	581.2	2.3446	0.2667	247.2	489.9	73 597.0	55 088.8	128 685.9
		4	755.6	581.1	2.3440	0.2661	247.4	490.4	73 675.1	55 092.0	128 767.1
		5	755.7	581.2	2.3446	0.2661	247.2	489.9	73 594.1	55 088.6	128 682.8
		6	753.0	576.0	2.3599	0.2667	237.9	465.9	70 273.4	48 971.3	119 244.7
		7	753.1	576.1	2.3605	0.2672	237.7	465.3	70 188.3	48 974.9	119 163.3
		8	753.0	576.0	2.3599	0.2672	237.9	465.9	70 269.7	48 971.5	119 241.2
	I	WD	683.0	537.1	2.0620	0.2578	354.0	772.3	–	–	144 260.5
		1	684.4	539.7	2.0543	0.2613	358.6	784.3	–	–	149 096.2
		2	681.6	534.5	2.0697	0.2543	349.4	760.3	–	–	139 492.9
3	D	WD	893.0	663.3	5.3184	0.1500	1003.6	134.7	113 810.9	175 913.4	289 724.3
		3	896.4	666.9	5.3305	0.1000	1018.9	139.1	115 790.6	183 470.9	299 261.5
		4	896.3	666.8	5.3305	0.0998	1019.4	139.3	115 847.0	183 474.8	299 321.8
		5	896.4	666.9	5.3305	0.0998	1018.9	139.1	115 786.7	183 470.8	299 257.5
		6	889.5	659.6	5.3072	0.1000	988.2	130.3	111 832.9	168 423.4	280 256.4
		7	889.6	659.7	5.3072	0.1002	987.7	130.2	111 768.4	168 427.6	280 195.9
		8	889.5	659.6	5.3072	0.1002	988.2	130.3	111 828.9	168 423.6	280 252.5
	I	WD	842.1	616.2	5.3289	0.3751	1234.5	206.3	–	–	304 883.4
		1	845.6	619.8	5.3405	0.3796	1249.9	210.7	–	–	314 513.6
		2	838.7	612.5	5.3173	0.3707	1219.1	201.9	–	–	295 382.5
4	D	WD	845.5	669.0	7.3010	0.2000	1004.9	245.8	125 036.7	112 689.0	237 725.7
		3	847.8	672.6	7.2894	0.1333	1014.4	255.6	126 981.4	119 412.1	246 393.5
		4	847.6	672.5	7.2882	0.1330	1014.8	256.0	127 047.1	119 416.0	246 463.1
		5	847.8	672.6	7.2894	0.1331	1014.4	255.6	126 977.6	119 412.0	246 389.7
		6	843.2	665.4	7.3147	0.1333	995.5	236.0	123 123.0	106 034.7	229 157.7
		7	843.3	665.4	7.3159	0.1336	995.2	235.6	123 049.3	106 038.7	229 088.0
		8	843.2	665.4	7.3147	0.1336	995.5	236.0	123 119.0	106 034.8	229 153.8
	I	WD	782.5	631.9	6.6974	0.1224	1157.4	441.4	–	–	255 134.3
		1	784.8	635.5	6.6848	0.1219	1166.9	451.3	–	–	263 874.8
		2	780.2	628.2	6.7100	0.1229	1147.9	431.6	–	–	246 499.7
5	D	WD	1034.9	847.9	7.3513	0.0500	1476.8	230.8	170 756.6	498 460.9	669 217.5
		3	1039.0	852.8	7.3597	0.0333	1491.5	236.5	172 797.4	512 598.4	685 395.8
		4	1038.9	852.7	7.3593	0.0333	1491.8	236.7	172 842.1	512 602.5	685 444.6
		5	1039.0	852.8	7.3597	0.0333	1491.5	236.5	172 793.4	512 598.4	685 391.7
		6	1030.8	843.0	7.3432	0.0333	1462.0	225.2	168 717.3	484 485.5	653 202.8
		7	1030.9	843.1	7.3435	0.0334	1461.7	225.0	168 664.3	484 489.7	653 153.9
		8	1030.8	843.0	7.3432	0.0334	1462.0	225.2	168 713.2	484 485.6	653 198.8
	I	WD	981.5	805.7	7.1629	0.1024	1642.7	309.2	–	–	681 436.2
		1	985.7	810.7	7.1711	0.1028	1657.4	314.9	–	–	697 666.0
		2	977.4	800.8	7.1546	0.1021	1627.9	303.6	–	–	665 375.2

TABLE 7. Parameter values for the numerical examples with government intervention.

No.	ζ_1	ζ_2	δ	S'
1	0.3	1.0	0.70	80 000
2	0.3	1.0	0.70	80 000
3	0.4	0.8	0.75	75 000
4	0.4	0.8	0.75	75 000
5	0.5	0.6	0.85	70 000

TABLE 8. The results of the numerical examples after disruption government intervention only on green products*.

Sample No.	Scenarios	P_1	P_2	θ	φ	$\Pi_r^{\mathrm{DS}^*}$	$\Pi_m^{\mathrm{DS}^*}$	Π^*	$\Pi_g^{\mathrm{DS}^*}$
1	5	543.7	609.8	2.155	0.033	1.237	1.373	2.610	1252.0
	8	538.7	605.3	2.141	0.033	1.201	1.285	2.486	1205.8
2	5	502.4	622.2	0.746	0.266	1.119	1.300	2.419	245.6
	8	498.7	617.4	0.752	0.267	1.086	1.218	2.303	240.0
3	5	681.9	758.2	2.824	0.100	2.012	5.294	7.306	2796.4
	8	674.5	752.4	2.782	0.100	1.976	5.084	7.059	2701.3
4	5	569.1	761.7	0.761	0.133	1.907	4.176	6.083	519.9
	8	563.7	755.4	0.751	0.134	1.869	3.997	5.866	501.9
5	5	732.2	1005.6	1.312	0.033	2.535	11.570	14.104	1034.3
	8	723.5	996.7	1.276	0.033	2.497	11.193	13.690	989.8

Notes. (*)The unit of profit functions are as $\times 10^5$.

TABLE 9. The results of the numerical examples after disruption government intervention only on green products*.

Sample No.	Type	I/D	Scenario 5 $\overline{\Pi}_m^{co-\mathrm{DE}}$	$\overline{\Pi}_s^{co-\mathrm{DE}}$	$\overline{\Pi}_c^{co-\mathrm{DE}}$	Scenario 8 $\overline{\Pi}_m^{co-\mathrm{DS}}$	$\overline{\Pi}_s^{co-\mathrm{DS}}$	$\overline{\Pi}_c^{co-\mathrm{DS}}$
1	Without contract	I	–	–	89 618.0	–	–	80 644.2
		D	9057.7	58 474.0	67 531.7	4061.8	54 672.0	58 733.9
	With contract	D	18 862.0	70 575.6	89 437.6	15 964.5	64 851.9	80 816.4
2	Without contract	I	–	–	149 096.2	–	–	139 492.9
		D	55 088.7	73 594.1	128 682.8	48 971.5	70 269.7	119 241.2
	With contract	D	73 552.6	75 343.8	148 896.4	68 497.6	71 154.2	139 651.8
3	Without contract	I	–	–	314 513.6	–	–	295 382.5
		D	183 470.8	115 786.7	299 257.5	168 423.6	111 828.9	280 252.5
	With contract	D	184 801.0	129 515.6	314 316.6	173 282.5	122 217.0	295 499.5
4	Without contract	I	–	–	263 874.8	–	–	246 499.7
		D	119 412.0	126 977.6	246 389.7	106 034.8	123 119.0	229 153.8
	With contract	D	127 817.7	135 906.6	263 724.3	116 615.6	130 019.6	246 635.1
5	Without contract	I	–	–	697 666.0	–	–	665 375.2
		D	512 598.4	172 793.4	685 391.7	484 485.6	168 713.2	653 198.8
	With contract	D	519 794.7	177 764.3	697 559.0	495 069.9	170 399.0	665 468.9

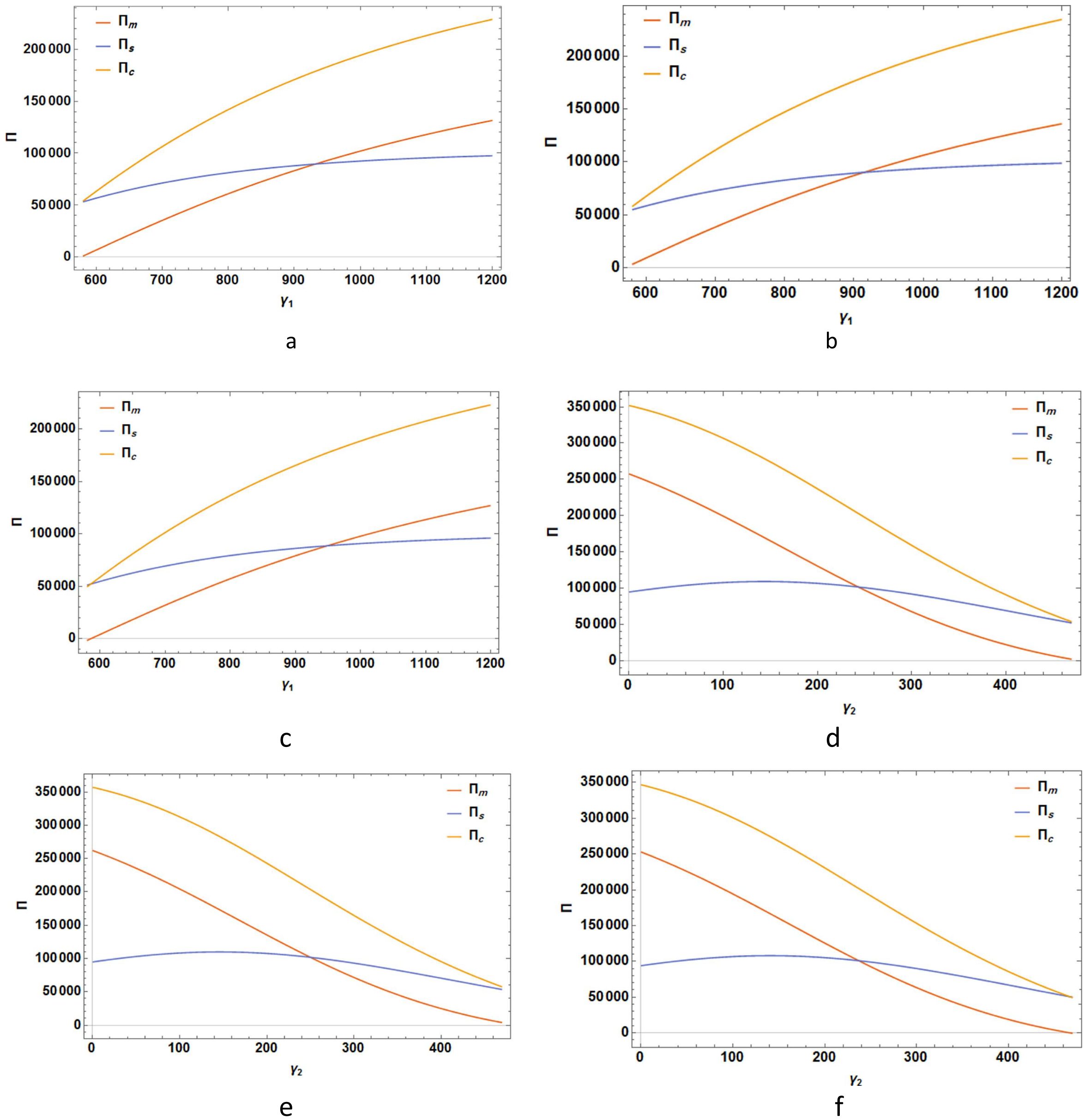

FIGURE 3. Profit values *versus* the elasticity of the greening level for the product (γ_i). (a) Without disruption (γ_1). (b) Scenario 5 (γ_1). (c) Scenario 8 (γ_1). (d) Without disruption (γ_2). (e) Scenario 5 (γ_2). (f) Scenario 8 (γ_2).

the supplier, while the slope for the manufacturer is more than the supplier. Figures 3b and 3c have the same explanations for Scenarios 5 and 8, respectively. Furthermore, Figure 3d illustrates the changes in the profit values in decentralized mode and without disruption when γ_2 changes. This figure suggests that an increase in γ_2 decrease the profit of both the manufacturer and the supplier, while the slope for the manufacturer is steeper than the supplier. Similar interpretations exist for Figures 3e and 3f. The main finding from the Figure 3 is

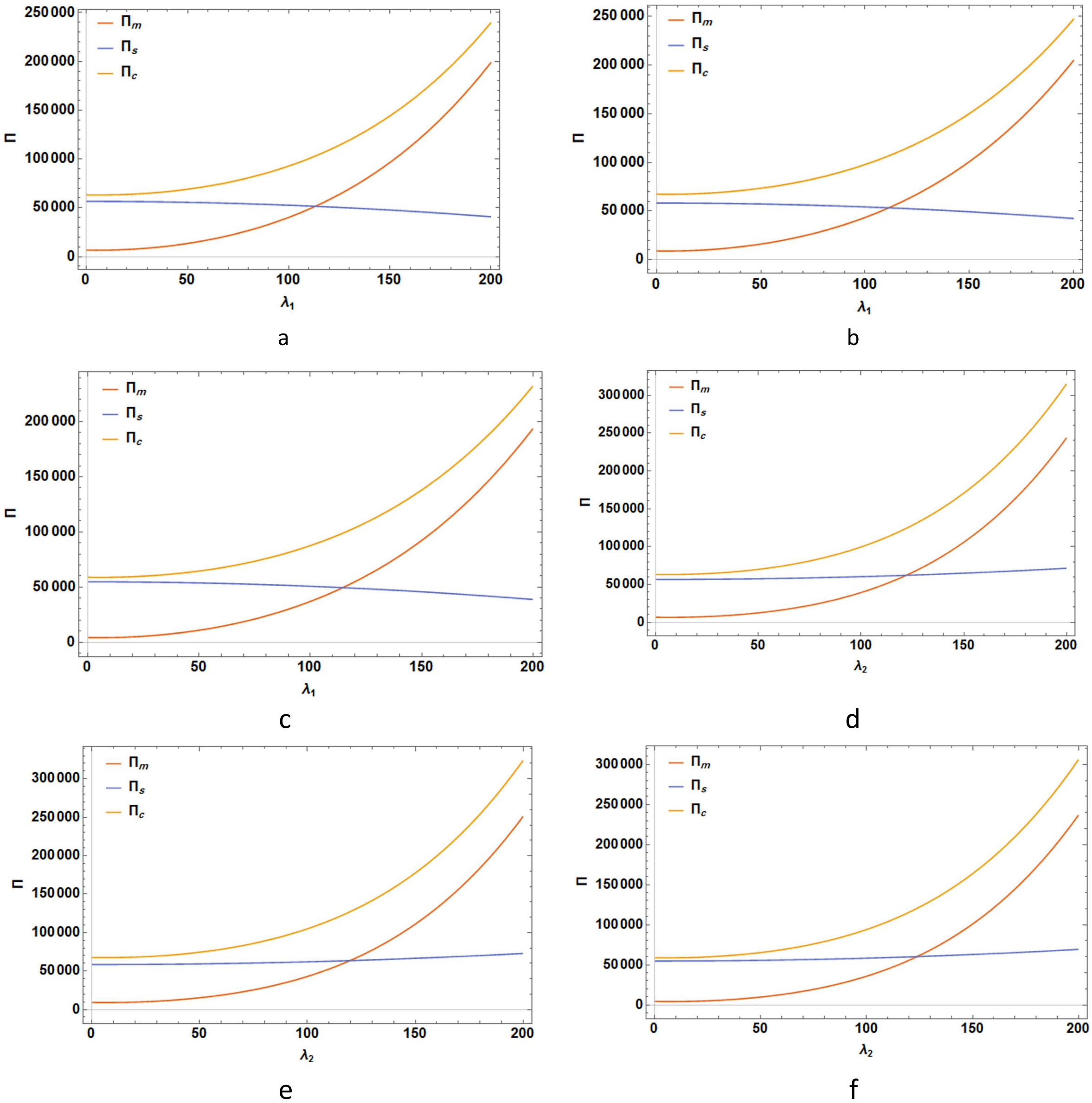

FIGURE 4. Profit values *versus* the elasticity of greening level for parts (λ_i). (a) Without disruption (λ_1). (b) Scenario 5 (λ_1). (c) Scenario 8 (λ_1). (d) Without disruption (λ_2). (e) Scenario 5 (λ_2). (f) Scenario 8 (λ_2).

that increasing the greening level of the products will directly increase the profit of the SC members with green products, and *vice versa*, will decrease the profit for SC members with non-green products.

Figure 4a illustrates the changes in the profit values when λ_1 changes for the decentralized model without disruption. The chart represents that an increase in λ_1 increases the manufacturer's profit while the supplier's profit will decrease. Figures 4b and 4c have the same explanations for Scenarios 5 and 8, respectively. Furthermore, Figure 4d illustrates the changes in the profit values for the decentralized mode without disruption

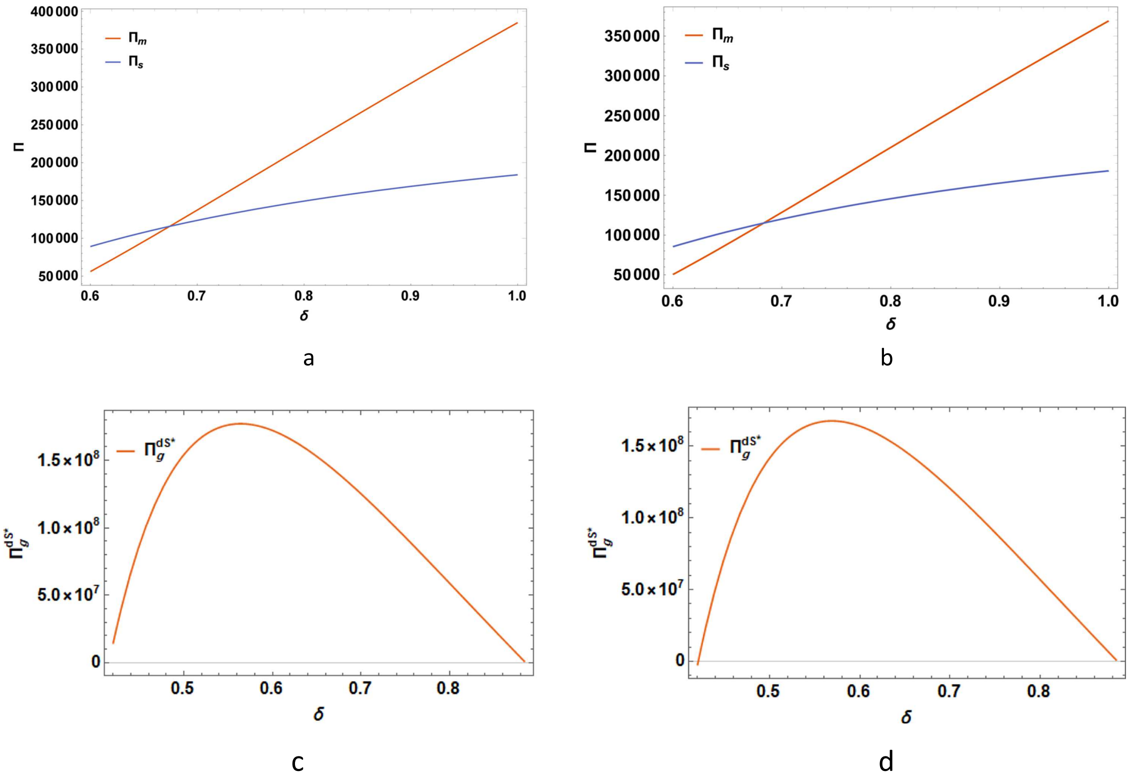

FIGURE 5. Profit values *versus* the elasticity of government intervention level (δ). (a) Scenario 5 – manufacturer and supplier. (b) Scenario 8 – manufacturer and supplier. (c) Scenario 5 – government. (d) Scenario 8 – government.

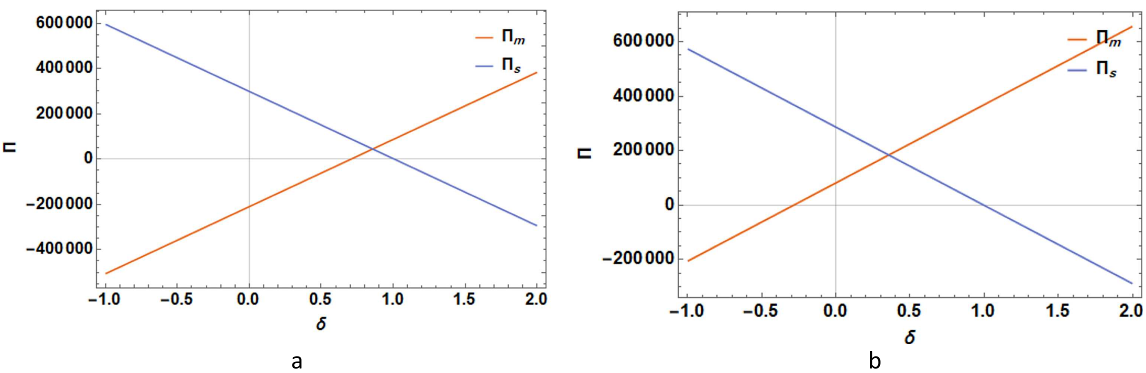

FIGURE 6. The profit value *versus* the elasticity of the ratio of cost for the supplier in the contract (Ω). (a) Scenario 5 – Cost Sharing contract. (b) Scenario 8 – Cost Sharing contract.

when λ_2 changes. The chart represents that an increase in λ_2 increases the manufacturer's profit, while that of the supplier does not experience a considerable change. Figures 4e and 4f illustrate the same trend for Scenarios 5 and 8 and then λ_2, respectively. The main finding from the Figure 4 is that increasing the greening level of the parts will directly increase the profit of the SC members with green products.

Figure 5a illustrates the changes in profit values of the manufacturer and the supplier when the GI level (δ) changes for Scenario 5, and Figure 5b illustrates similar information for Scenario 8. The charts show that the profit values increases by increasing δ. The profit value of the supplier is larger than that of the manufacturer for small amounts of δ; however,the profit gained by the supplier would be higher than that of the manufacturer for larger amounts of δ. Figures 5c and 5d represent the utility functions of the government *versus* δ for Scenarios 5 and 8. Both utility functions are concave concerning δ. The main finding from the Figure 5 is that increasing the government intervention level will first increase the utility function of the government, and then will decrease it. It means there are an optimum point for the government for interving the SC, where after this point, the government utility will decrease.

Figure 6a illustrates profit values for the manufacturer and supplier *versus* the ratio of the cost for the supplier in the contract (Ω) for Scenario 5, while Figure 6b illustrates similar information for Scenario 8. The charts show that by increasing Ω, the profit value of the manufacturer increases while that of the supplier decreases. The main finding from the Figure 6 is that there are a breakeven point in cost-sharing contract, between the profit of the manufacturer and the supplier, where before it, the profit of supplier is higher than the profit of manufacturer. After that, the profit of manufacturer will be higher than the supplier one.

8. Managerial insights

In this section, some managerial insights have been collected to provide decision-making solutions.

- Focusing on producing green cars in disturbed conditions can create a competitive advantage for car manufacturers that can protect their market share under these conditions.
- It should be noted that investing in the production of green cars would increase the price of green cars compared to regular cars, such as Toyota, Nissan, and Renault (www.cars.com). Therefore, the car manufacturer should look for the optimal equilibrium point to increase the level of greenery and car prices so as not to lose its demand in the market.
- According to the model and the results, when the government supports the production of green cars, the price of cars in the market has decreased, and the demand for green cars has increased. In Europe, the government gives various kinds of incentives to the customer to encourage them to buy Battery Electric Vehicles (BEV) or hybrid one. The same situation is in China, USA, and the other developed countries (www.iea.org). This has resulted in increased profits for manufacturers and suppliers. Therefore, the government's cooperation and support strategy in the event of disruption can help maintain the chain's survival in the market.
- According to the results, it is shown that in the integrated model of manufacturer and supplier, the overall profit of the chain increases. Therefore, one way to deal with the consequences of chain disruption is the integrated cooperation of members to overcome the crisis.
- Since, in the integrated model, one of the members may be harmed, the coordination contracts between the members can be used to maintain integrity.
- Increasing the greening level of the products will directly increase the profit of the SC members with green products, and *vice versa*, will decrease the profit for SC members with non-green products.
- Increasing the greening level of the parts will directly increase the profit of the SC members with green products.
- Increasing the government intervention level will first increase the utility function of the government, and then will decrease it. It means there are an optimum point for the government for interving the SC, where after this point, the government utility will decrease.
- There are a breakeven point in cost-sharing contract, between the profit of the manufacturer and the supplier, where before it, the profit of supplier is higher than the profit of manufacturer. After that, the profit of manufacturer will be higher than the supplier one.

9. Conclusion

This paper studied a two-stage green ASC that is disrupted by risk events, where the SC consists of one manufacturer and one supplier with two kinds of products (green and non-green). Both products are supplied by the supplier and produced by the manufacturer. The greening effort is considered for both the supplier and the manufacturer. Consider a situation in which all SC members are inside a country, and disruption disrupts cross-border transport activities. Furthermore, direct/indirect GI in automotive industries is considered in both economic and social forms, which is implemented through subsidy-taxation policies to the manufacturer to develop the green product. The effects of this intervention and DRs were investigated in this study, and it was supposed that the manufacturer was more potent than the supplier. Channel coordination through a cost-sharing contract during disruption was studied here. This paper developed a mathematical model with the aim of profit maximization in both integrated and decentralized systems. The model examined the effects of greening efforts on SC members with eight scenarios. Moreover, GI and channel coordination through the cost-sharing contract considering disruption developed. To examine the proposed model, five numerical examples are applied. The scenarios indicated that Extra Production type of risk would increase the profitability, whereas those indicated Surplus Inventory type of risk would decrease the profitability. Moreover, GI and cost-sharing contracts increase the SC profit.

For future investigation, the other kinds of contract would be used to facilitate to relationship between SC members.

Appendix A.

$$
\begin{aligned}
T_1 = {} & (2\beta_1\gamma_2^2 + \rho_1(2\gamma_2^2 + \tau\rho_1) + 2\beta_2(\gamma_1^2 - 2\tau(\beta_1 + \rho_1)) + 2\gamma_1^2\rho_2 - 2\tau(2\beta_1 + \rho_1)\rho_2 + \tau\rho_2^2 \\
& - 2\gamma_1\gamma_2(\rho_1 + \rho_2)
\end{aligned} \tag{A.1}
$$

$$
\begin{aligned}
T_2 = {} & \lambda_1^2(2C_1\tau(\beta_2 + \rho_2) - C_1\gamma_2^2) + \lambda_1\lambda_2(C_1(\gamma_1\gamma_2 - \tau(\rho_1 + \rho_2)) + C_2(\gamma_2^2 - 2\tau(\beta_2 + \rho_2))) \\
& + C_2\lambda_2^2(\tau(\rho_1 + \rho_2) - \gamma_1\gamma_2) + a_1h(\gamma_2^2 - 2\tau(\beta_2 + \rho_2)) + a_2h(\gamma_1\gamma_2 - \tau(\rho_1 + \rho_2)) \\
& + W_1(h(2\beta_2\gamma_1^2 + \gamma_2^2(\beta_1 + \rho_1)) + \lambda_1^2(\gamma_2^2 + 2(h\rho_2 - \tau(\rho_2 - \beta_2))) + \lambda_1\lambda_2(\tau(\rho_1 + \rho_2) - \gamma_1\gamma_2) \\
& + h\tau(\rho_1(\rho_1 - 2\beta_2) - \rho_2(2\beta_1 + \rho_1) - 2\beta_1\beta_2) - h\gamma_1\gamma_2(\rho_2 + 2\rho_1)) + W_2(\lambda_1\lambda_2(2\tau(\beta_2 + \rho_2) - \gamma_2^2) \\
& + \gamma_1\gamma_2(\lambda_2^2 - h(\beta_2 + \rho_2)) + \gamma_2^2h\rho_1 - \tau\lambda_2^2(\rho_1 + \rho_2) + h\tau((\beta_2 + \rho_2)(\rho_2 - \rho_1))) \\
& + A_1(h(2\gamma_1^2(\beta_2 + \rho_2) + \gamma_2^2(\beta_1 + \rho_1) - \gamma_1\gamma_2(2\rho_1 + \rho_2)) + h\tau(\rho_1(\rho_1 - 2\beta_2 - \rho_2) - 2\beta_1(\rho_2 + \beta_2)))
\end{aligned} \tag{A.2}
$$

$$
T_3 = \gamma_1\gamma_2 - \tau(\rho_1 + \rho_2) \tag{A.3}
$$

$$
\begin{aligned}
T_4 = {} & \lambda_2^2(2C_2\tau(\beta_1 + \rho_1) - C_2\gamma_1^2) - a_1h\tau(\rho_1 + \rho_2) + \lambda_1^2(C_1\tau\rho_1 + C_1\tau\rho_2) - \tau\lambda_1\lambda_2(2C_1\rho_1 + C_2(\rho_1 + \rho_2)) \\
& + a_2h(\gamma_1^2 - 2\tau(\beta_1 + \rho_1)) + W_1(\gamma_1\gamma_2(\lambda_1^2 - h(\beta_1 + \rho_1)) + \lambda_1\lambda_2(2\tau(\beta_1 + \rho_1) - \gamma_1^2) \\
& + h\tau(\rho_1(\beta_1 + \rho_1) - \beta_1\rho_2) - \tau\lambda_1^2(\rho_1 + \rho_2) + \gamma_1^2) + W_2(\gamma_1^2(\beta_2h + \gamma_1^2 + h\rho_2) + 2\gamma_2^2(h(\beta_1 + \rho_1)) \\
& - 2\tau\lambda_2^2(\beta_1 + \rho_1) - \gamma_1\gamma_2h(\rho_1 + 2\rho_2) + \lambda_1\lambda_2(\tau(\rho_1 + \rho_2) - \gamma_1\gamma_2) + h\tau(\rho_2(\rho_2 - \rho_1 - 2\beta_1) \\
& - 2\beta_2(\beta_1 + \rho_1))) + A_1(h\tau((\beta_1 + \rho_1)(\rho_1 - \rho_2)) - \gamma_1\gamma_2h(\beta_1 + \rho_1) + \gamma_1^2h\rho_2) \\
& + hA_2(-\gamma_1\gamma_2\rho_1 + 2\gamma_2^2(\beta_1 + \rho_1) + \beta_2(\gamma_1^2 - 2\tau(\beta_1 + \rho_1)) + \gamma_1(\gamma_1 - 2\gamma_2)\rho_2 - \tau(2\beta_1 + \rho_1)\rho_2 + \tau\rho_2^2)
\end{aligned} \tag{A.4}
$$

$$
\begin{aligned}
T_5 = {} & \lambda_1\lambda_2(\rho_1(\gamma_2(2C_1 + C_2) - C_1\gamma_1) + \rho_2(C_2\gamma_2 - \gamma_1(C_1 + 2C_2))) + \lambda_1^2(C_1(2\gamma_1\rho_2 - \gamma_2(\rho_1 + \rho_2))) \\
& + \lambda_2^2(C_2(\gamma_1(\rho_2 + \rho_1) - 2\gamma_2\rho_1)) + a_2h(2\gamma_2(\beta_1 + \rho_1) - \gamma_1(\rho_1 + \rho_2)) + a_1h(-2\beta_2\gamma_1 - 2\gamma_1\rho_2 \\
& + \gamma_2(\rho_1 + \rho_2)) + W_1(\gamma_1h(2\beta_2(\beta_1 + \rho_1) + \rho_2(2\beta_1 - \rho_2)) + \gamma_2h(\beta_1(\rho_2 - \rho_1) - \rho_1^2) \\
& + \lambda_1\lambda_2(\gamma_1(\rho_1 + \rho_2) - 2\gamma_2(\beta_1 + \rho_1)) + \lambda_1^2(\rho_2(\gamma_2 - 2\gamma_1) - 2\beta_2\gamma_1 + \gamma_2\rho_1) + h\rho_1\rho_2(\gamma_1 + \gamma_2)) \\
& - hA_2(2\beta_1\gamma_2(\beta_2 + \rho_2) - (\rho_1 - \rho_2)(\gamma_2\rho_1 - \gamma_1\rho_2) + \beta_2(\gamma_1(\rho_1 + \rho_2) - 2\gamma_2\rho_1)) + W_2(\lambda_2^2(2\gamma_2(\beta_1 + \rho_1) \\
& - \gamma_1(\rho_1 + \rho_2)) + \lambda_1\lambda_2(2\gamma_1(\beta_2 + \rho_2) - \gamma_2(\rho_1 + \rho_2)) + h(\rho_1(\gamma_2\rho_1 - \beta_2(\gamma_1 + 2\gamma_2)) + \rho_2(\gamma_1(\beta_2 + \rho_2)
\end{aligned}
$$

$$- 2\beta_1\gamma_2) - \rho_1\rho_2(\gamma_1 + \gamma_2) - 2\beta_1\beta_2\gamma_2)) + A_1(h(\gamma_1(2\beta_2(\beta_1 + \gamma_1\rho_1) + \rho_2(2\beta_1 + \rho_1))$$
$$+ \gamma_2((\rho_2 - \rho_1)(\beta_1 + \rho_1))) - \gamma_1\rho_2^2) \quad (A.5)$$

$$T_6 = -\tau\lambda_2^2(C_1(\beta_1 + \rho_1) + C_2\rho_1 + a_1) - \gamma_2^2 h\rho_1(C_1 + C_2) - C_1(h\tau\rho_1^2 - 2\rho_2(\gamma_1^2 h + \tau\lambda_1^2))$$
$$+ h\gamma_1\gamma_2(\rho_2(C_1 + C_2) + 2C_1\rho_1) + h\tau\rho_2(2a_1 + \rho_1(C_1 + C_2) - C_2\rho_2) + \tau\lambda_1\lambda_2(\rho_2(C_1 + C_2)$$
$$+ 2C_1\rho_1) + a_2(\tau(h(\rho_1 + \rho_2) - \lambda_1\lambda_2) - \gamma_1\gamma_2) + A_1(\gamma_2^2(\lambda_1^2 - h(\beta_1 + \rho_1)) + \lambda_2^2(\gamma_1^2 - \tau(\beta_1 + \rho_1))$$
$$+ h\gamma_1\gamma_2(2\rho_1 + \rho_2) + \lambda_1\lambda_2(k(2\rho_1 + \rho_2) - 2\gamma_1\gamma_2) - 2\rho_2(\gamma_1^2 h + \tau\lambda_1^2) + h\tau(\rho_2(2\beta_1 + \rho_1) - \rho_1^2))$$
$$+ A_2(\gamma_2 h(\gamma_1\rho_2 - \gamma_2\rho_1) + \tau(\lambda_1\lambda_2\rho_2 - \lambda_2^2\rho_1 + h(\rho_1 - \rho_2)\rho_2)) + \beta_2(\gamma_1\gamma_2 h(C_2 + A_2) + 2a_1 h\tau$$
$$+ 2C_1(h\tau(\beta_1 + \rho_1) - \gamma_1^2 h - \tau\lambda_1^2) + C_2 k(\gamma_1\gamma_2 + h(\rho_1 - \rho_2)) + 2A_1(h\tau(\beta_1 + \rho_1) - \gamma_1^2 h - \tau\lambda_1^2)$$
$$+ \tau A_2(\lambda_1\lambda_2 + h(\rho_1 - \rho_2))) \quad (A.6)$$

$$T_7 = \lambda_1\lambda_2(\tau C_1(\beta_1 + \rho_1) - a_1\tau + C_2(\tau(\rho_1 + 2\rho_2) - 2\gamma_1\gamma_2)) + C_2\lambda_2^2(\gamma_1^2 - 2\tau(\beta_1 + \rho_1))$$
$$+ h\gamma_1\gamma_2(C_1(\rho_1 + \beta_1) + C_2(\rho_1 + 2\rho_2) - a_1) - 2C_2\gamma_2^2 h(\beta_1 + \rho_1) - \gamma_1^2 h\rho_2(C_1 + C_2)$$
$$- a_2(\gamma_1^2 h + \tau(\lambda_1^2 - 2h(\beta_1 + \rho_1))) + h\tau(\rho_2(a_1 + C_1(\beta_1 + \rho_1) + C_2(2\beta_1 + \rho_1(1 - \rho_2 a_1)))$$
$$- C_1\rho_1(\beta_1 + \rho_1)) + A_2(\gamma_2^2(\lambda_1^2 - 2h\rho_1) + \lambda_2(\gamma_1^2\lambda_2 + \tau(\lambda_1 - 2\lambda_2)\rho_1) + \rho_2(\tau(h\rho_1 - \lambda_1(\lambda_1 - 2\lambda_2))$$
$$- \gamma_1^2 h) - h\tau\rho_2^2 + \gamma_1\gamma_2(h(\rho_1 + 2\rho_2) - 2\lambda_1\lambda_2) - 2\beta_1(\gamma_2^2 h + \tau(\lambda_2^2 - h\rho_2))) + \lambda_1^2(C_2(\gamma_2^2 - \tau\rho_2)$$
$$- C_1\tau\rho_2) + A_1((\beta_1 + \rho_1)(h\gamma_1\gamma_2 + \tau\lambda_1\lambda_2) - \rho_2(\gamma_1^2 h + \tau\lambda_1^2) + h\tau(\rho_1(\rho_2 - \beta_1 - \rho_1) + \beta_1\rho_2))$$
$$- \beta_2(C_2 + A_2)(\gamma_1^2 h + \tau(\lambda_1^2 - 2h(\beta_1 + \rho_1))) \quad (A.7)$$

$$T_8 = \gamma_2^2(\lambda_1^2 - 2h\rho_1) + \lambda_2^2(\gamma_1^2 - 2\tau\rho_1) + 2\gamma_1\gamma_2(\rho_1(h + \tau) - 2\lambda_1\lambda_2) - h\tau(\rho_1^2 + \rho_2^2) - 2\beta_2(\gamma_1^2 h + \tau(\lambda_1^2$$
$$- 2h(\beta_1 + \rho_1))) - 2\beta_1(\gamma_2^2 h + \tau\lambda_2^2 - 2h\tau\rho_2) + 2\rho_2(\gamma_1(\gamma_2 - \gamma_1)h + \tau\lambda_1(\lambda_2 - \lambda_1) + h\tau\rho_1) \quad (A.8)$$

$$T_9 = \gamma_2\lambda_1^2(a_2 - \beta_2 C_2 + \rho_2(C_1 - C_2)) + \lambda_1\lambda_2((C_2 - C_1)(\gamma_1\rho_2 + \gamma_2\rho_1)) + \gamma_1 h\rho_2^2(C_1 - C_2)$$
$$+ \gamma_1(\rho_1(h(a_2 - \beta_2(2C_1 + C_2)) + \lambda_2^2(C_1 - C_2)) + \lambda_1\lambda_2(\beta_2 C_2 - a_2) + h\rho_2(a_2 - \beta_2 C_2))$$
$$+ \gamma_2 h\rho_1(C_2(2\beta_2 - \rho_1) - 2a_2 + C_1\rho_1) + a_1(2\beta_2\gamma_1 h + \gamma_2\lambda_1\lambda_2 - \gamma_2 h(\rho_1 + \rho_2) - \gamma_1(\lambda_2^2 - 2h\rho_2))$$
$$+ h\rho_1\rho_2(\gamma_1(C_2 - C_1) + \gamma_2(C_2 - C_1)) + A_1(\rho_1(\gamma_1(\lambda_2^2 - 2\beta_2 h) + \gamma_2(h\rho_1 - \lambda_1\lambda_2)) + \rho_2(\gamma_2\lambda_1^2$$
$$- h\rho_1(\gamma_1 + \gamma_2) + \gamma_1(h\rho_2 - \lambda_1\lambda_2))) + A_2(\beta_2(\lambda_1(\gamma_1\lambda_2 - \gamma_2\lambda_1) + h(\gamma_1(\rho_1 - \rho_2) + 2\gamma_2\rho_1))$$
$$+ \gamma_1(\lambda_1\lambda_2\rho_2 + h\rho_2(\rho_1 - \rho_2)) + \gamma_2(\rho_1 - \rho_2) - \lambda_2^2\rho_1) + \beta_1(C_1\gamma_1\lambda_2^2 + \gamma_2(C_1(h\rho_1 - \lambda_1\lambda_2) - 2a_2 h)$$
$$+ h\rho_2(2C_2\gamma_2 - C_1(2\gamma_1 + \gamma_2)) + A_1(\gamma_1(\lambda_2^2 - 2\rho_2) - \gamma_2\lambda_1\lambda_2 + h(\gamma_2(\rho_1 - \rho_2))) + 2\gamma_2 h\rho_2 A_2$$
$$+ 2\beta_2 h(\gamma_2(C_2 + A_2) - \gamma_1(C_1 + A_1))) \quad (A.9)$$

$$T_{10} = \lambda_1(\gamma_2^2(\beta_1 C_1 - a_1 + \rho_1(C_2 - C_1)) + \tau\rho_2(2a_1 - 2\beta_1 C_1 + \rho_2(C_1 - C_2))) + \gamma_1\gamma_2(\lambda_2(a_1 - \beta_1 C_1$$
$$+ \rho_1(C_2 - C_1)) + \lambda_1\rho_2(C_2 - C_1)) + \lambda_2(\tau\rho_1(\beta_1 C_1 - a_1 + \rho_1(C_1 - C_2)) + \tau\rho_1\rho_2(C_2 - C_1)$$
$$\times (\lambda_1 + \lambda_2) + \rho_2(\gamma_1^2(C_1 - C_2) + \tau(\beta_1(2C_2 - C_1) - a_1))) + a_2(-\gamma_1\gamma_2\lambda_1 + \gamma_1^2\lambda_2 - 2\tau\lambda_2(\beta_1 + \rho_1)$$
$$+ \tau\lambda_1(\rho_1 + \rho_2)) + A_1(\lambda_1(\gamma_2^2(\beta_1 + \rho_1) + \tau\rho_2(\rho_2 - 2\beta_1)) - \gamma_1\gamma_2(\lambda_2(\beta_1 + \rho_1) + \lambda_1\rho_2)$$
$$+ \lambda_2(\tau\rho_1(\beta_1 + \rho_1) + \rho_2(\gamma_1^2 - \tau\beta_1)) - \tau\rho_1\rho_2(\lambda_1 + \lambda_2)) + A_2(\rho_2(\gamma_1\gamma_2\lambda_1 + \lambda_2(2\beta_1\tau - \gamma_1^2)$$
$$+ \tau\rho_1(\lambda_1 + \lambda_2)) - \tau\lambda_1\rho_2^2 - \rho_1(\gamma_2^2\lambda_1 + \lambda_2(\tau\rho_1 - \gamma_1\gamma_2))) + \beta_2(C_2(\gamma_1\gamma_2\lambda_1 - \gamma_1^2\lambda_2 + 2\tau\lambda_2(\beta_1 + \rho_1)$$
$$+ \tau\lambda_1(\rho_1 - \rho_2)) + 2\tau\lambda_1(a_1 - (\beta_1 + \rho_1)(C_1 + A_1)) + A_2(\gamma_1\gamma_2\lambda_1 - \gamma_1^2\lambda_2 + 2\tau\lambda_2(\beta_1 + \rho_1)$$
$$+ \tau\lambda_1(\rho_1 - \rho_2))) \quad (A.10)$$

$$T_{11} = \beta_2 - a_2(\beta_2\gamma_1^2 h + \beta_1\gamma_1\gamma_2 h + \beta_1\tau\lambda_1\lambda_2 + \beta_2\tau(\lambda_1^2 - 2h(\beta_1 + \rho_1)) - \beta_1 h\tau(\rho_1 + \rho_2)) + \beta_1(-a_1(\gamma_2^2 h$$
$$+ \tau(\lambda_2^2 - 2h\rho_2)) + \beta_1(\gamma_2^2 h + \tau\lambda_2^2 - 2h\tau\rho_2)(C_1 + A_1) + ((\gamma_2^2 h + \tau\lambda_2^2)\rho_1 - (\gamma_1\gamma_2 h + \tau\lambda_1\lambda_2$$
$$+ h\tau\rho_1)\rho_2 + h\tau\rho_2^2)(C_1 - C_2 + A_1 - A_2)) + \beta_2(a_1(-\gamma_1\gamma_2 h - \tau\lambda_1\lambda_2 + h\tau(2\beta_1 + \rho_1 + \rho_2))$$
$$- 2\beta_1^2 h\tau(C_1 + A_1) - (C_1 - C_2 + A_1 - A_2)(-\gamma_1\gamma_2 h\rho_1 + \gamma_1^2 h\rho_2 + \tau(h\rho_1(\rho_1 - \rho_2) + \lambda_1^2\rho_2 - \lambda_1\lambda_2\rho_1))$$
$$+ \beta_1(C_1\gamma_1\gamma_2 h + C_2(\gamma_1\gamma_2 h + \tau\lambda_1\lambda_2 + h\tau(\rho_1 - 3\rho_2)) + C_1\tau(\lambda_1\lambda_2 + h(\rho_2 - 3\rho_1)) + A_1(\gamma_1\gamma_2 h$$

$$+ \tau\lambda_1\lambda_2 + h\tau(\rho_2 - 3\rho_1)) + A_2(\gamma_1\gamma_2 h + \tau\lambda_1\lambda_2 + h\tau(\rho_1 - 3\rho_2)) \tag{A.11}$$

$$\begin{aligned} T_{12} = {} & (\gamma_1\gamma_2 h + \tau\lambda_1\lambda_2 - h\tau(\rho_1+\rho_2))(h\tau(a_2 + C_2(\beta_2+\rho_2) - C_1\rho_1 + A_2(\beta_2 - \rho_1 + \rho_2)) + \gamma_2 h(C_1\gamma_1 + \gamma_1 A_1 \\ & - \gamma_2(C_2 + A_2)) + \tau\lambda_2(C_1\lambda_1 + \lambda_1 A_1 - \lambda_2(C_2 + A_2))) + (\tau(\lambda_2^2 - 2h(\beta_2+\rho_2)) + \gamma_2^2 h)(h\tau(a_1 + (\beta_1+\rho_1) \\ & \times (C_1 + A_1) - \rho_2(C_2 + A_2)) + \gamma_1 h(\gamma_2(C_2 + A_2) - \gamma_1(A_1 + C_1)) + \tau\lambda_1(\lambda_2(C_2 + A_2) \\ & - \lambda_1(A_1 + C_1))) \end{aligned} \tag{A.12}$$

$$T_{13} = \lambda_1\lambda_2 - h(\rho_1+\rho_2) \tag{A.13}$$

$$\begin{aligned} T_{14} = {} & (E_m^I(h\tau(\beta_2 - T_{31}) + \gamma_2 h T_{17} + \tau\lambda_2 T_{22}) + \Delta a_2^{\mathrm{IE}} h\tau) + (h\tau(E_m^I(T_{21} - \rho_2) + \Delta a_1^{\mathrm{IE}}) \\ & + \gamma_1 h E_m^I((\gamma_2 - \gamma_1) + \tau\lambda_1(\lambda_2 - \lambda_1))) \end{aligned} \tag{A.14}$$

$$\begin{aligned} T_{15} = {} & E_m^I(h\gamma_1\gamma_2(\beta_1 + 2T_{27}) + \gamma_2^2 T_{16} - 2\gamma_1^2 h\rho_2 - \lambda_1\lambda_2(2\gamma_1\gamma_2 + \tau(\beta_1 + 2T_{27})) + h\tau(\rho_2(3\beta_1 + 2\rho_1 - \rho_2 \\ & - 2\tau\lambda_1^2) + 2\beta_2 T_{21} - \rho_1 T_{21}) + \lambda_2^2 T_{20}) \end{aligned} \tag{A.15}$$

$$T_{16} = \lambda_1^2 - 2h(\beta_1+\rho_1) \tag{A.16}$$

$$T_{17} = \gamma_1 - \gamma_2 \tag{A.17}$$

$$T_{18} = \rho_2 + \beta_2 \tag{A.18}$$

$$T_{19} = \beta_2(-E_m^I(\lambda_2(\gamma_1^2 - 2\rho_1) - \lambda_1(\gamma_1\gamma_2 - T_{27}) + \tau(2\beta_1(\lambda_1 - \lambda_2)))) + \Delta a_1^{\mathrm{IE}}(\lambda_2 T_3 + \lambda_1(2\tau T_{18} - \gamma_2^2)) \tag{A.19}$$

$$T_{20} = \gamma_1^2 - 2\tau(\rho_1+\beta_1) \tag{A.20}$$

$$T_{21} = \beta_1 + \rho_1 \tag{A.21}$$

$$T_{22} = \lambda_1 - \lambda_2 \tag{A.22}$$

$$T_{23} = (hT_3 + \tau\lambda_1\lambda_2)(\Delta a_2^{\mathrm{IS}} h\tau + S_m^c(\tau(\rho_1 - T_{18}) + \gamma_2(\gamma_2 - \gamma_1)) + \tau\lambda_2(S_m^I(\lambda_2 - \lambda_1))) \tag{A.23}$$

$$\begin{aligned} T_{24} = {} & S_m^I(\gamma_2^2(2hT_{21} - \lambda_1^2) + \lambda_1\lambda_2(2T_3 - \tau\beta_1) + h\tau(\beta_1(\rho_1 - 3\rho_2) + {T_{31}}^2 - 2\beta_2 T_{21}) + 2\rho_2(\gamma_1^2 h + \tau\lambda_1^2) \\ & + \lambda_2^2(2\tau T_{21} - \gamma_1^2) - h\gamma_1\gamma_2(2T_{27} - \beta_1)) \end{aligned} \tag{A.24}$$

$$\begin{aligned} T_{25} = {} & -\beta_1(-S_m^I(\gamma_2 T_{13} + \gamma_1(\lambda_2^2 - 2h\rho_2) + 2\beta_2 h(\gamma_2 - \gamma_1))2\Delta a_2^{\mathrm{IS}}\gamma_2 h) \\ & + \Delta a_1^{\mathrm{IS}}(\gamma_2 T_{13} + \gamma_1(2h(\gamma_1\rho_2 + \beta_2) - \lambda_2^2)) \end{aligned} \tag{A.25}$$

$$T_{26} = \beta_2(S_m^I(\gamma_1(\gamma_1\lambda_2 - \gamma_2\lambda_1) + \tau(2\beta_1 T_{22} - 2\lambda_2\rho_1 + \lambda_1 T_{27})) + (\beta_1 S_m^I + \Delta a_1^{\mathrm{IS}})(\lambda_2 T_3 + T_{24}) \tag{A.26}$$

$$T_{27} = \rho_1 + \rho_2 \tag{A.27}$$

$$\begin{aligned} T_{28} = {} & -(-a_1\beta_2\gamma_1\gamma_2 h - \beta_1(a_1\gamma_2^2 h + C_2\tau\lambda_2^2\rho_2) + C_1\lambda_1^2(\beta_1\gamma_2^2 - \tau(\beta_2(2\beta_1 + \rho_1 + \rho_2) + 2\beta_1\rho_2) + \beta_2) \\ & + C_2\lambda_2^2(\beta_2(\gamma_1^2 - \tau\rho_1) + \beta_1(\gamma_1\gamma_2 - \tau(2\beta_2 + \rho_1))) + \lambda_1\lambda_2(C_1(\tau\rho_1(\beta_1 + 2\beta_2) - \beta_2\gamma_1^2) \\ & - \gamma_1\gamma_2(\beta_1 C_1 - \beta_2 C_2) + \tau C_2(\beta_1(2(\rho_2 + \beta_2) + C_1\tau\rho_2) + \beta_2\rho_2)) + h\tau(2a_1\beta_1\rho_2 + a_1\beta_2(\rho_1 + \rho_2)) \\ & + W_1(h\tau(\beta_1(\beta_2(\rho_2 - 3\rho_1) - 2\beta_1(\rho_2 + \beta_2) + \rho_2(\rho_2 - \rho_1)) + \beta_2\rho_1(\rho_2 - \rho_1)) + h(\gamma_2^2(\beta_1(\beta_1 + \rho_1)) \\ & - \beta_2\gamma_1^2\rho_2) + \lambda_1^2(\beta_2\tau(2\beta_1 + \rho_1 + \rho_2) + \beta_1(2\tau\rho_2 - \gamma_2^2)) + \lambda_1\lambda_2(\beta_2(\gamma_1^2 - 2\tau\rho_1) + \beta_1(\gamma_1\gamma_2 - \tau(2\beta_2 \\ & + \rho_1 - \rho_2))) + \gamma_1\gamma_2(h(\beta_2(\rho_1 + \beta_1) - \beta_1\rho_2) - \beta_2\lambda_1^2)) + W_2(\lambda_1\lambda_2(\beta_2(\gamma_1\gamma_2 - \tau(2\beta_1 + \rho_1 + \rho_2)) \\ & + \beta_1(\gamma_2^2 - 2k\rho_2)) + \lambda_2^2(\beta_1(\tau(\rho_1 + \rho_2 + 2\beta_2) - \gamma_1\gamma_2) + \beta_2(2\tau\rho_1 - \gamma_1^2)) + h(\gamma_1\gamma_2(\beta_1(\rho_2 + \beta_2) \\ & - \beta_2\rho_1) - \beta_1\gamma_2^2\rho_1 + \beta_2\gamma_1^2(\beta_2 + \rho_2)) + h\tau(\rho_1\rho_2(\beta_1 - \beta_2) - \beta_1(\rho_2^2 + \beta_2(3\rho_2 + 2\beta_2)) + \beta_2\rho_1(\rho_1 + \beta_1 \\ & - 2\beta_2\rho_1))) + hA_1(\gamma_1\gamma_2(\beta_1(\beta_2 - \rho_2) + \beta_2\rho_1) + \beta_1\gamma_2^2(\beta_1 + \rho_1) - \beta_2(\tau\rho_1^2 + \gamma_1^2\rho_2) - 2\beta_1^2\tau(\rho_2 + \beta_2) \\ & + \tau(\beta_1(\beta_2(\rho_2 - 3\rho_1) + \rho_2^2) + \rho_1\rho_2(\beta_2 - \beta_1))) + h(\beta_2^2(\gamma_1^2 - 2\tau(\beta_1 + \rho_1)) + \beta_2 A_2((\beta_1\gamma_1\gamma_2 - \gamma_1\gamma_2\rho_1 \\ & + \beta_1\tau(\rho_1 - 3\rho_2) + \tau\rho_1(\rho_1 - \rho_2) + \gamma_1^2\rho_2) + \beta_1(-\gamma_2^2\rho_1 + \gamma_1\gamma_2\rho_2 + \tau\rho_2(\rho_1 - \rho_2))))) \end{aligned} \tag{A.28}$$

$$\begin{aligned} T_{29} = {} & -(\gamma_2^2(C_1\lambda_1^2 - \tau a_1) + C_2\lambda_2^2(\gamma_1\gamma_2 - \tau(\rho_1 + \rho_2)) + 2\rho_2\tau(a_1\tau - C_1\lambda_1^2) + \lambda_1\lambda_2(C_1\tau(\rho_1 + \rho_2) \\ & - C_1\gamma_1\gamma_2 + C_2(2\tau\rho_2 - \gamma_2^2)) + a_2\tau(-\gamma_1\gamma_2 + \tau(\rho_1 + \rho_2)) + W_1(\gamma_1\gamma_2(\tau(2\rho_1 + \rho_2) + \lambda_1\lambda_2) \\ & - \gamma_2^2(\tau(\beta_1 + \rho_1) + \lambda_1^2) - \tau\lambda_1\lambda_2(\rho_1 + \rho_2) - \tau^2\rho_1^2 + \rho_2(2(\beta_1\tau - \gamma_1^2 + \lambda_1^2) + \tau\rho_1)) + W_2(\lambda_1\lambda_2(\gamma_2^2 \end{aligned}$$

$$- 2\tau\rho_2) - \gamma_2^2\tau\rho_1 + \tau\lambda_2^2(\rho_1+\rho_2) + \gamma_1\gamma_2(\tau\rho_2 - \lambda_2^2) + \tau^2\rho_2(\rho_1-\rho_2)) + \tau A_1(\gamma_1\gamma_2(2\rho_1+\rho_2) - \gamma_2^2(\beta_1+\rho_1) - \tau\rho_1^2 + \rho_2(\tau(2\beta_1+\rho_1) - 2\gamma_1^2)) + \tau A_2(\rho_2(\gamma_1\gamma_2 + \tau(\rho_1-\rho_2)) - \gamma_2^2\rho_1) + \beta_2 k(2\lambda_1(C_2\lambda_2 - C_1\lambda_1) + 2W_1(\tau(\beta_1+\rho_1)+\lambda_1^2) + W_2(k(\rho_1-\rho_2) - 2\lambda_1\lambda_2) + 2\tau A_1(\beta_1+\rho_1) - 2\gamma_1^2(W_1+A_1) + \tau A_2(\rho_1-\rho_2) + \gamma_1\gamma_2(W_2+A_2))) \tag{A.29}$$

$$T_{30} = 2\tau(a_1 + \Delta a_1^{\mathrm{DE}}) + E_m^D\tau(2\beta_1 + 3\rho_1 - \rho_2) - \tau\Delta a_2^{\mathrm{DE}}T_3 + \tau\Delta a_1^{\mathrm{DE}}(2\tau\rho_2 - \gamma_2^2) + \beta_2\tau(E_m^D\gamma_1(\gamma_2 - 2\gamma_1) \tag{A.30}$$

$$T_{31} = \rho_1 - \rho_2 \tag{A.31}$$

$$T_{32} = -(\gamma_1\gamma_2(\tau a_1 + C_1\lambda_1^2) + \lambda_1\lambda_2(C_1(2\tau(\beta_1+\rho_1) - \gamma_1^2) + C_2(\tau(\rho_1+\rho_2) - \gamma_1\gamma_2)) + \rho_2(a_1\tau - C_1\lambda_1^2) + C_2\lambda_2^2(\gamma_1^2 - 2\tau(\beta_1+\rho_1)) + \rho_1(a_1\tau - C_1\lambda_1^2) + a_2\tau(2\tau(\beta_1+\rho_1) - \gamma_1^2) + W_1(\gamma_1\gamma_2(\tau(\beta_1+\rho_1) - \lambda_1^2) + \lambda_1\lambda_2(\gamma_1^2 - 2\tau(\beta_1+\rho_1)) + \tau\lambda_1^2\rho_1 - \gamma_1^2\tau\rho_2 + \tau^2(\beta_1(\rho_2-\rho_1) + \rho_1(\rho_2-\rho_1)) + \tau\lambda_1^2\rho_2) + W_2(\tau^2(2\beta_1(\beta_2+\rho_2) + \rho_1(2\beta_2+\rho_2) - \rho_2^2) - \gamma_1^2\tau(\beta_2+\rho_2) - 2\gamma_2^2\tau(\beta_1-\rho_1) + \lambda_1\lambda_2(\gamma_1\gamma_2 - \tau(\rho_1+\rho_2)) + \lambda_2^2(2\tau(\beta_1+\rho_1) - \gamma_1^2) + \tau\gamma_1\gamma_2(\rho_1+2\rho_2)) + \tau A_1(\gamma_1\gamma_2(\beta_1+\rho_1) - \tau\rho_1(\beta_1+\rho_1) - \gamma_1^2\rho_2 + \rho_2(\tau(\beta_1+\rho_1))) + \tau A_2(\rho_2(2\gamma_1\gamma_2 + \tau(2\beta_1+\rho_1) - \gamma_1^2)\gamma_1\gamma_2\rho_1 - 2\gamma_2^2(\beta_1+\rho_1) - \tau\rho_2^2 + \beta_2(2\tau(\beta_1+\rho_1) - \gamma_1^2))) \tag{A.32}$$

$$T_{33} = -(C_2\lambda_2^2(2\gamma_2(\beta_1+\rho_1) - \gamma_1(\rho_1+\rho_2)) + \tau(a_2\gamma_1(\rho_1+\rho_2) - 2a_2\gamma_2(\beta_1+\rho_1)) + C_1\lambda_1^2(\gamma_2(\rho_1+\rho_2) - 2\gamma_1\rho_2) + \lambda_1\lambda_2(C_1(\gamma_1(\rho_1+\rho_2) - 2\gamma_2(\beta_1+\rho_1)) + C_2(2\gamma_1\rho_2 - \gamma_2(\rho_1+\rho_2))) + a_1\tau(2\beta_2\gamma_1 + 2\gamma_1\rho_2 - \gamma_2(\rho_1+\rho_2)) + W_1(\lambda_1\lambda_2(2\gamma_2(\beta_1+\rho_1) - \gamma_1(\rho_1+\rho_2)) + \gamma_2\tau(\rho_1(1+\rho_1) - \beta_1\rho_2) + \lambda_1^2(2\gamma_1\rho_2 - \gamma_2(\rho_1+\rho_2)) - \tau\rho_1\rho_2(\gamma_1+\gamma_2) + \gamma_1\tau\rho_2(\rho_2 - 2\beta_1)) + W_2(\gamma_2\lambda_1\lambda_2(\rho_1+\rho_2) + \lambda_2^2(\gamma_1(\rho_1+\rho_2) - 2\gamma_2(\beta_1+\rho_1)) - \tau(\gamma_2(\rho_1^2 + 2\beta_1\rho_2) - \gamma_1\rho_2^2) + \tau\rho_1\rho_2(\gamma_1+\gamma_2)) + \tau A_1(\gamma_2(\rho_1(\beta_1+\rho_1) - \beta_1\rho_2) - \rho_2(\gamma_1(2\beta_1 + \tau\rho_2) + \rho_1(\rho_1+\rho_2))) + \tau A_2(\rho_2(2\beta_1\gamma_2 + \gamma_1(\rho_1-\rho_2)) + \gamma_2\rho_1(\rho_2-\rho_1)) + \beta_2(-2C_1\gamma_1\lambda_1^2 + 2C_2\gamma_1\lambda_1\lambda_2 + 2\gamma_1 W_1(\lambda_1^2 - \tau(\beta_1+\rho_1)) + W_2(\tau(2\gamma_2(\beta_1+\rho_1) + \gamma_1(\rho_1-\rho_2)) - 2\gamma_1\lambda_1\lambda_2) - 2\gamma_1\tau A_1(\beta_1+\rho_1) + \tau A_2(2\gamma_2(\beta_1+\rho_1) + \gamma_1(\rho_1-\rho_2)))) \tag{A.33}$$

$$T_{34} = \beta_2(2\Delta a_1^{\mathrm{DE}}\gamma_1\tau + \tau E_m^D(\rho_1(2\gamma_2-\gamma_1) - \gamma_1\rho_2) + \gamma_2(W_2+A_2)) + \tau\Delta a_1^{\mathrm{DE}}(\rho_2(2\gamma_1-\gamma_2) - \gamma_2\rho_1) + \tau A_2(2\gamma_2(\rho_1 - \beta_1) + \gamma_1 T_{31}) + \tau\Delta a_2^{\mathrm{DE}}(\gamma_1 T_{27} - 2\gamma_2 T_{21}) + \tau E_m^D(\beta_1\gamma_2 T_{27} - 2\beta_1\gamma_1\rho_2) \tag{A.34}$$

$$T_{35} = (\gamma_1\gamma_2 - \tau(\rho_1+\rho_2))(\tau(a_2 - \rho_1(W_1+A_1)) + \lambda_2(C_1\lambda_1 - (C_2\lambda_2 + \lambda_1 W_1)) + W_2(\tau(\beta_2+\rho_2) + \lambda_2^2) + \gamma_2(\gamma_1(W_1+A_1) - \gamma_2(W_2+A_2)) + \tau A_2(\beta_2+\rho_2)) + (\gamma_2^2 - 2\tau(\beta_2+\rho_2))(a_1\tau - C_1\lambda_1^2 + C_2\lambda_1\lambda_2 + W_1(\tau(\beta_1+\rho_1) + \lambda_1^2) - W_2(\lambda_1\lambda_2 - \tau\rho_2) + \tau(A_1(\beta_1+\rho_1) - \rho_2 A_2) + \gamma_1(\gamma_2(W_2+A_2) - \gamma_1(W_1+A_1))) \tag{A.35}$$

$$T_{36} = E_s^D(\lambda_1\lambda_2(\gamma_1(\rho_1 + 3\rho_2 + 2\beta_2) - \gamma_2(3\rho_1 + \rho_2 + 2\beta_1))) + \tau\Delta a_2^{\mathrm{DE}}(\gamma_1 T_{27} - 2\gamma_2 T_{21}) + \tau\Delta a_1^{\mathrm{DE}}(2\gamma_1 T_{18} - \gamma_2 T_{27}) \tag{A.36}$$

$$T_{37} = E_c^D(\beta_2 k(2a_1\tau + E_c^D(\gamma_1(\gamma_2 - 2\gamma_1) + 2\lambda_1(\lambda_2-\lambda_1) + \tau(2\beta_1 + 3\rho_1 - \rho_2))) - \tau\lambda_2^2 T_{27} - (\tau T_{31})^2 + \lambda_1\lambda_2(\tau(\rho_1 + 3\rho_2) - \gamma_2^2)) + \tau\Delta a_1^{\mathrm{DE}}(2\tau T_{18} - \gamma_2^2) - \tau\Delta a_2^{\mathrm{DE}}T_3 \tag{A.37}$$

$$T_{38} = E_c^D(\gamma_1\gamma_2(\tau(\beta_1 + 2T_{27}) - \lambda_1\lambda_2 + \lambda_1^2) - 2\beta_1\gamma_2^2\tau + \lambda_1\lambda_2(\tau(2\beta_1 + 3\rho_1 + \rho_2) - \gamma_1^2) + \lambda_2^2(\gamma_1^2 - 2\tau T_{21}) - \tau\rho_1(2\gamma_2^2 - \tau T_{21}) - \tau\lambda_1^2 T_{27} + \tau\rho_2(\tau(3\beta_1 + 2\rho_1 - \rho_2)) - 2\gamma_1^2) - \beta_2\tau T_{20}(E_c^D + W_2 + A_2) - \tau\Delta a_1^{\mathrm{DE}}T_3 + \tau\Delta a_2^{\mathrm{DE}}(2\tau T_{21} - \gamma_1^2) + \beta_2\tau W_2 T_{20} \tag{A.38}$$

$$T_{39} = -(a_2\tau(\gamma_1(\rho_1+\rho_2) - 2\gamma_2\rho_1) + C_1\lambda_1^2(\gamma_2(\rho_1+\rho_2) - 2\gamma_1(\beta_2+\rho_2)) + \lambda_1\lambda_2(C_1(\gamma_1(\rho_1+\rho_2) - 2\gamma_2\rho_1) + C_2(2\gamma_1(\beta_2+\rho_2) - \gamma_2(\rho_1+\rho_2))) + C_2\lambda_2^2(2\gamma_2\rho_1 - \gamma_1(\rho_1+\rho_2)) + a_1\tau(2\gamma_1(\beta_2+\rho_2) - \gamma_2(\rho_1+\rho_2)) + W_1(\lambda_1^2(2\gamma_1(\beta_2+\rho_2) - \gamma_2(\rho_1+\rho_2)) + \lambda_1\lambda_2(2\gamma_2\rho_1 - \gamma_1(\rho_1+\rho_2)) + \tau(\rho_1(\gamma_2 - 2\beta_2\gamma_1) + \gamma_1\rho_2^2)$$

$$
\begin{aligned}
&- \tau\rho_1\rho_2(\gamma_1+\gamma_2)) + W_2(\tau(\gamma_2(2\beta_2\rho_1-\rho_1^2)+\gamma_1(\beta_2(\rho_1-\rho_2)-\rho_2^2)) + \lambda_2^2(\gamma_1(\rho_1+\rho_2)-2\gamma_2\rho_1)\\
&+ \lambda_1\lambda_2(\gamma_2(\rho_1+\rho_2)-2\gamma_1(\rho_2+\beta_2)) + \tau\rho_1\rho_2(\gamma_1+\gamma_2)) + \tau A_1(\gamma_2\rho_1^2+\gamma_1(\rho_2^2-2\beta_2\rho_1)-\rho_1\rho_2(\gamma_1+\gamma_2))\\
&+ \tau A_2(2\beta_2\gamma_2\rho_1+\beta_2\gamma_1(\rho_1-\rho_2)-(\rho_1-\rho_2)(\gamma_2\rho_1-\gamma_1\rho_2)) + \beta_1(2\gamma_2(\tau(\rho_2 A_2-a_2)+C_2\lambda_2^2)\\
&- 2C_1\gamma_2\lambda_1\lambda_2 + W_1(2\gamma_2\lambda_1\lambda_2-2\gamma_1\rho_2+\tau(\gamma_2(\rho_1-\rho_2))) + 2\gamma_2 W_2(\tau\rho_2-\lambda_2^2) + \tau A_1(\gamma_2(\rho_1-\rho_2)\\
&- 2\gamma_1\rho_2) + 2\beta_2\tau(\gamma_2(W_2+A_2)-\gamma_1(W_1+A_1)))) \qquad \text{(A.39)}
\end{aligned}
$$

$$
\begin{aligned}
T_{40} &= E_c^D(\lambda_1\lambda_2(\gamma_1(2\beta_2+\rho_1+3\rho_2)-\gamma_2(3\rho_1+\rho_2-\beta_1(\tau T_{31}+2))) + \rho_1(\beta_2\tau(2\gamma_2-\gamma_1)-2\gamma_2)\\
&+ \lambda_1^2(\gamma_2 T_{27}-2\gamma_1 T_{18}) + \lambda_2^2(2\gamma_2 T_{21}-\gamma_1 T_{27}) - \gamma_1\tau\rho_2(\beta_1+\beta_2)) + \tau A_2(\beta_2(2\gamma_2\rho_1+\gamma_1 T_{31})\\
&- T_{31}(\gamma_2\rho_1-\gamma_1\rho_2)) - \beta_1 2\beta_2\tau E_c^D T_{17} \qquad \text{(A.40)}
\end{aligned}
$$

$$
\begin{aligned}
T_{41} &= S_s^D(\lambda_1\lambda_2(\gamma_2(2\beta_1+3\rho_1+\rho_2)-\gamma_1(\rho_1+2\beta_2+3\rho_2)) + \lambda_2^2(\gamma_1 T_{27}-2\gamma_2 T_{21}) + \lambda_1^2(2\gamma_1 T_{18}-\gamma_2 T_{27}))\\
&+ \tau\Delta a_1^{\mathrm{DS}}(2\gamma_1 T_{18}-\gamma_2 T_{27}) \qquad \text{(A.41)}
\end{aligned}
$$

$$
\begin{aligned}
T_{42} &= \lambda_1\lambda_2(\gamma_1\gamma_2+\gamma_2^2-\tau\rho_1\gamma_1(2\gamma_1-\gamma_2)-3k\rho_2) + \tau^2(\rho_1-\rho_2)^2\tau(\rho_2-2\beta_1-3\rho_1) + \tau\rho_2(2(\gamma_1^2-\beta_1\tau\\
&+ \lambda_1^2)+\lambda_2^2) + S_c^D(\lambda_2^2(\tau T_{21}-\lambda_1^2) + 2\lambda_1(\lambda_1-\lambda_2) + 2\gamma_2^2\tau\rho_1) + \gamma_1\gamma_2(W_2+A_2-2\tau(\rho_1-\rho_2)+\lambda_2^2) \qquad \text{(A.42)}
\end{aligned}
$$

$$
\begin{aligned}
T_{43} &= S_c^D(\tau(2\gamma_2^2 T_{21}+\beta_1\tau(\rho_1-3\rho_2)+\lambda_1^2 T_{27}+2\gamma_1^2\rho_2) - \gamma_1\gamma_2(\lambda_1^2+\tau(2T_{27}+\beta_1)) + \lambda_2^2(2\beta_1\tau-\gamma_1^2+2\tau\rho_1)\\
&+ \lambda_1\lambda_2(\gamma_1(\gamma_1+\gamma_2)-\tau(2\beta_1-3\rho_1-\rho_2)) + \tau^2(\rho_1-\rho_2)^2) + \tau\Delta a_2^{\mathrm{DS}}(2\tau T_{21}-\gamma_1^2) - \tau^2\Delta a_1^{\mathrm{DS}} T_3\\
&- 2\tau W_2(\beta_1\gamma_2^2-\beta_2\tau\rho_1) + \beta_2\tau(\gamma_1^2-2\tau T_{21}) + \beta_2\tau(\gamma_1^2-2\tau T_{21}) \qquad \text{(A.43)}
\end{aligned}
$$

$$
\begin{aligned}
T_{44} &= S_c^D(\rho_1(\gamma_2(3-2\beta_2\tau)+\beta_2\gamma_1(\tau+2\lambda_1^2)+\lambda_2^2(\gamma_1-2\gamma_2)) + \lambda_1\lambda_2(2\beta_1\gamma_2-2\beta_2\gamma_1-\gamma_1\rho_1\\
&+ \rho_2(\gamma_2-3\gamma_1+\beta_2\gamma_1\tau+\lambda_1^2(2\gamma_1-\gamma_2)))) + \tau\beta_1(S_c^D(2\gamma_1 k\rho_2-\gamma_2(2\lambda_2^2-\tau T_{27})+2\beta_2\tau(\gamma_1-\gamma_2)) \qquad \text{(A.44)}
\end{aligned}
$$

$$
\begin{aligned}
T_{45} &= (\Delta a_2^{\mathrm{DE}}\tau + C_1\lambda_1\lambda_2 - C_2\lambda_2^2 + E_c^D((\gamma_1-\gamma_2)\gamma_2-((\lambda_1-\lambda_2)\lambda_2+\tau(\beta_2-\rho_1+\rho_2))(\delta-1)) + \delta(C_2\lambda_2^2\\
&- \Delta a_2^{\mathrm{DE}}\tau - C_1\lambda_1\lambda_2) + \tau a_2(1-\delta) + W_1((1-\delta)(\gamma_1\gamma_2-\lambda_1\lambda_2)+\tau\rho_1(\delta(2-\delta))-1) + W_2((1-\delta)\\
&\times(\tau(\beta_2+\rho_2)+\lambda_2^2)-\gamma_2^2) + A_1(\gamma_1\gamma_2+\tau\rho_1(\delta-1)) - A_2(\gamma_2^2+\tau(\beta_2+\rho_2)(\delta-1)))(\gamma_1\gamma_2\delta+\tau(\delta-1)\\
&\times(\rho_2+\rho_1\delta)) + ((\delta-1)(E_c^D(\tau(\rho_2-\beta_1-\rho_1)+\lambda_1\delta(\lambda_1-\lambda_2)) + \delta(C_1\lambda_1^2-\tau(a_1+\Delta a_1^{\mathrm{DE}})-C_2\lambda_1\lambda_2)\\
&+ W_1(\delta(\tau(\beta_1+\rho_1)-\lambda_1^2)-\tau(\beta_1+\rho_1)) + W_2(\tau\rho_2+\lambda_1\lambda_2\delta) + \tau(\rho_2 A_2-A_1(\beta_1+\rho_1))))\\
&\times(\gamma_2^2+2\tau(\beta_2+\rho_2)(\delta-1)) \qquad \text{(A.45)}
\end{aligned}
$$

$$
\begin{aligned}
T_{46} &= (\tau(1-\delta))^2(2\delta(\gamma_2(\gamma_2(\beta_1+\rho_1)-\gamma_1\rho_2)+\gamma_1(\gamma_1(\beta_2+\rho_2)-\gamma_2\rho_1)\delta) - \tau(\delta-1)(\rho_2^2-2\rho_2\delta(2\beta_1+\rho_1)\\
&+ \delta(\rho_1^2\delta-4\beta_2(\beta_1+\rho_1)))) \qquad \text{(A.46)}
\end{aligned}
$$

$$
\begin{aligned}
T_{47} &= (\tau(2\delta(\gamma_1\gamma_2(\rho_2+\rho_1\delta)-\gamma_2^2(\beta_1+\rho_1)-\gamma_1^2\delta(\beta_2+\rho_2)) + \tau(\delta-1)(\rho_2^2-2\rho_2\delta(2\beta_1+\rho_1)\\
&+ \delta(\rho_1^2\delta-4\beta_2(\beta_1+\rho_1))))) \qquad \text{(A.47)}
\end{aligned}
$$

$$
\begin{aligned}
T_{48} &= (1-\delta)(\tau\delta(\rho_1(2C_2\lambda_2^2-2a_2\tau+\delta(C_1\lambda_1^2-a_1\tau))+\rho_2(C_1\lambda_1^2-a_1\tau))) + \delta^2(a_2\tau-C_2\gamma_1^2\lambda_2^2)\\
&+ \delta\lambda_1\lambda_2(\gamma_1\delta(C_2\gamma_2+C_1\gamma_1)-\tau(1-\delta)(C_2(\rho_2+\rho_1\delta)+2C_1\rho_1)) + \gamma_1\gamma_2\delta^2(a_1\tau-C_1\lambda_1^2)\\
&+ W_1(\lambda_1\lambda_2\delta(2\tau\rho_1(1-\delta)-\gamma_1^2\delta) + \rho_1\rho_2(\tau^2(\delta(2-\delta)-1)) + \gamma_1\gamma_2\delta(\lambda_1^2\delta+\tau\rho_1(\delta-1)) + \tau\delta(\tau\rho_1^2(1-\delta)^2\\
&+ \gamma_1^2\rho_2(1-\delta)) + \tau\lambda_1^2\delta(\delta-1)(\rho_2+\rho_1\delta)) + W_2(\tau\delta(2\rho_1(\gamma_2^2-\beta_2 k-\lambda_2^2)-\gamma_1\gamma_2(2\rho_2+\rho_1\delta)\\
&+ \lambda_1\lambda_2((1-\delta)(\rho_2+\rho_1\delta)) - \tau\rho_2^2 + \delta(\gamma_1^2(\beta_2+\rho_2)+2\rho_1(\beta_2\tau+\lambda_2^2)) + \tau\rho_1\rho_2(\delta-1)) + \tau\rho_2^2\\
&+ \gamma_1\lambda_2\delta^2(\gamma_1\lambda_2-\gamma_2\lambda_1)) + A_1(\tau\gamma_1\delta(\gamma_1\rho_2-\gamma_2\rho_1)+\tau^2\rho_1(\delta-1)(\rho_2-\rho_1\delta)) - \tau A_2(\tau(\delta-1)(\rho_2^2\\
&- \rho_1\delta(2\beta_2+\rho_2)) + \gamma_1\delta(\gamma_2(2\rho_2+\rho_1\delta)-\gamma_1\delta(\beta_2+\rho_2)) - 2\gamma_2^2\rho_1\delta) + \delta W_2(2(1-\delta)(\tau(\beta_2+\rho_2)+\lambda_2^2)\\
&- 2\gamma_2^2) - \beta_1\tau(2C_1\lambda_1\lambda_2\delta - 2C_2\lambda_2^2\delta - 2a_2\tau(\delta-1)\delta - 2C_1\lambda_1\lambda_2\delta^2 + 2C_2\lambda_2^2\delta^2 + W_1(\tau(\rho_2(1+\delta(\delta-2))\\
&- \rho_1\delta(\delta-1)^2) + \delta(1-\delta)(\gamma_1\gamma_2-2\lambda_1\lambda_2)) + A_1(\tau(1-\delta)(\rho_2-\rho_1\delta)+\gamma_1\gamma_2\delta)\\
&- 2\delta A_2(\gamma_2^2+\tau(\beta_2+\rho_2)(\delta-1))) \qquad \text{(A.48)}
\end{aligned}
$$

$$
T_{49} = -E_c^D(\tau^2(\delta-1)(\rho_2^2+\rho_1^2\delta-\rho_1(\rho_2+\delta(2\beta_2+\rho_2)))\gamma_1\delta^2(\lambda_1-\lambda_2)(\gamma_2\lambda_1-\gamma_1\lambda_2) + \tau\delta(\gamma_1\gamma_2(\rho_1(\delta+1)
$$

$$+ 2(\rho_2 - \gamma_2^2\rho_1)) + (\lambda_1 - \lambda_2)(\delta - 1)(\lambda_1(\rho_2 + \rho_1\delta) - 2\lambda_2\rho_1) - \gamma_1^2(\rho_2 + \delta(\beta_2 + \rho_2)))) + \tau\delta\Delta a_2^{\mathrm{DE}}(\gamma_1^2\delta + 2\tau\rho_1(\delta - 1)) - \beta_1\tau(2\Delta a_2^{\mathrm{DE}}\tau\delta(1 - \delta)) + E_c^D((\gamma_1 - 2\gamma_2)\gamma_2\delta - (\delta - 1)(2\lambda_2\delta + \tau(\rho_2 + \delta(2\beta_2 - \rho_1 + 2\rho_2)))) \tag{A.49}$$

$$T_{50} = \delta(C_2\lambda_2^2(2\gamma_2\rho_1 - \gamma_1\rho_2) - 2a_2\gamma_2\tau\rho_1 + \rho_2(\tau(a_2\gamma_1 - a_1\gamma_2) + C_1\gamma_2\lambda_1^2) + \delta(\gamma_1(2(\beta_2 + \rho_2)(\tau a_1 - 2C_1\lambda_1^2) + \rho_1(\tau a_2 - C_2\lambda_2^2)) + \gamma_2\rho_1(C_1\lambda_1^2 - \tau a_1)) + \lambda_1\lambda_2(\delta(C_2(2\gamma_1(\beta_2 + \rho_2) - \gamma_2\rho_1) + C_1\gamma_1\rho_1) + C_1(\gamma_1\rho_2 - 2\gamma_2\rho_1) - C_2\gamma_2\rho_2)) + W_1(\lambda_1\lambda_2\delta(2\gamma_2\rho_1 - \gamma_1(\rho_2 + \rho_1\delta)) + \lambda_1^2\delta(\gamma_2\rho_2 + \delta(2\gamma_1(\rho_2\beta_2) - \gamma_2\rho_1)) + \tau(\delta - 1)(\rho_1(\rho_2(\gamma_2 + \gamma_1\delta) + \delta(2\beta_2\gamma_1 - \gamma_2\rho_1)) - \gamma_1\rho_2^2)) + \delta W_2(\tau\rho_1(\gamma_2(2\beta_2 - \rho_1\delta) + \beta_2\gamma_1\delta) - \gamma_1\tau\rho_2(\beta_2 + \rho_2) + \tau\rho_1\rho_2(\gamma_2 + \gamma_1\delta) + \lambda_1\lambda_2(\gamma_2\rho_2 + \delta(\gamma_2\rho_1 - 2\gamma_1(\beta_2 + \rho_2))) + \lambda_2^2(\gamma_1(\rho_1\delta + \rho_2) - 2\gamma_2\rho_1)) + \tau A_1(\gamma_1\rho_2^2 - \rho_1\rho_2(\gamma_2 + \gamma_1\delta) + \rho_1\delta(\gamma_2\rho_1 - 2\beta_2\gamma_1)) + \tau\delta A_2((\gamma_1\rho_2 - \gamma_2\rho_1)(\rho_1\delta - \rho_2) + \beta_2(\rho_1(\gamma_1\delta + 2\gamma_2) - \gamma_1\rho_2)) + \beta_1(2\delta\gamma_2(C_2\lambda_2(\lambda_2 - C_1\lambda_1) - a_2\tau) + 2\tau\gamma_2\delta A_2(\beta_2 + \rho_2) + W_1(\delta(\gamma_2(2\lambda_1\lambda_2 + \tau(\rho_1(1 - \delta) + \rho_2)) + 2\gamma_1(\rho_2 + \beta_2)(\delta - 1) - \gamma_2\rho_2)) + 2\delta\gamma_2W_2(\tau(\rho_2 + \beta_2) - \lambda_2^2) + \tau A_1(\delta(\gamma_2\rho_1 - 2\gamma_1(\rho_2 + \beta_2)) - \gamma_2\rho_2)) \tag{A.50}$$

$$T_{51} = \tau\delta\Delta a_2^{\mathrm{DE}}(E_c^D(\beta_2\delta - 2\beta_2\gamma_1\tau\rho_1\delta - \gamma_1\tau(\rho_2(\delta - 1))(\rho_2 - \rho_1\delta) + \gamma_2\tau\rho_1((1 - \delta)(\rho_1 - \rho_2) + 2\beta_2) + \gamma_2\delta(\lambda_1 - \lambda_2)(\lambda_1(\rho_2 + \rho_1\delta) - 2\lambda_2\rho_1) + \gamma_1\delta(\lambda_1 - \lambda_2)(\lambda_2(\rho_2 + \rho_1\delta) - 2\lambda_1\delta(\beta_2 + \rho_2))) + \gamma_1(\rho_2 + \rho_1\delta) - 2\gamma_2\rho_1 + \beta_1(\delta E_c^D(2\beta_2\tau(\gamma_2 - \gamma_1) + 2\gamma_2\lambda_2(\lambda_2 - \lambda_1) - 2\gamma_1\tau\rho_2 + \gamma_2\tau(\rho_1 + 2\rho_2)) - \gamma_2\tau(E_c^d\rho_2 - 2\Delta a_2^{\mathrm{DE}}\delta))) \tag{A.51}$$

$$T_{52} = \tau(\delta - 1)((-\gamma_1\gamma_2\delta - \tau(\delta - 1)(\rho_2 + \rho_1\delta))(\Delta a_2^{\mathrm{DS}}\tau + C_1\lambda_1\lambda_2 - C_2\lambda_2^2 + S_c^D(\gamma_2^2 - \gamma_1\gamma_2 + ((\lambda_1 - \lambda_2)\lambda_2 + \tau(\beta_2 - \rho_1 + \rho_2))(\delta - 1)) + W_1(1 - \delta)(\gamma_1\gamma_2 - \lambda_1\lambda_2 - \tau\rho_1(1 - \delta)) + W_2((1 - \delta)(\tau(\beta_2 + \rho_2) + \lambda_2^2) - \gamma_2^2) + A_1(\gamma_1\gamma_2 - \tau\rho_1(1 - \delta)) - A_2(\delta - 1)(\gamma_2^2 + \tau(\beta_2 + \rho_2))) + (\gamma_2^2 + 2\tau(\beta_2 + \rho_2)(\delta - 1))(S_c^D(\delta - 1) \times (\tau(\rho_2 - \beta_1 - \rho_1) + \lambda_1\delta(\lambda_1 - \lambda_2)) + (\delta - 1)(\delta(\lambda_1(C_2\lambda_2 - C_1\lambda_1) - \tau(a_1 + \Delta a_1^{\mathrm{DS}})) + W_1(\lambda_1^2\delta - \tau(1 + \delta)(\beta_1 + \rho_1)) - W_2(\tau\rho_2 + \lambda_1\lambda_2\delta) + \tau A_1(\beta_1 + \rho_1) - \tau\rho_2A_2) - \gamma_1\delta(S_c^D(\gamma_1 - \gamma_2) + \gamma_1W_1(\delta - 1) - \gamma_1A_1 + \gamma_2(W_2 + A_2))) \tag{A.52}$$

$$T_{53} = \tau\delta\Delta a_2^{\mathrm{DS}}(\gamma_1^2\delta + 2\tau\rho_1(\delta - 1)) - S_c^D(\gamma_1(\lambda_1 - \lambda_2)(-\gamma_2\lambda_1 + \gamma_1\lambda_2)\delta^2 - \tau^2(\delta - 1)(\rho_2^2 + \rho_1^2\delta - \rho_1(\rho_2 + 2\beta_2\delta + \rho_2\delta)) + \tau\delta(2\gamma_2^2\rho_1 - \gamma_1\gamma_2(\rho_1 + 2\rho_2 + \rho_1\delta) - (\lambda_1 - \lambda_2)(\delta - 1)(-2\lambda_2\rho_1 + \lambda_1\rho_2 + \lambda_1\rho_1\delta) + \gamma_1^2(\rho_2 + (\beta_2 + \rho_2)\delta)))) - \beta_1\tau(2\Delta a_2^{\mathrm{DS}}\tau\delta(1 - \delta) + S_c^D(\gamma_2\delta(-\gamma_1 + 2\gamma_2) + (\delta - 1)(2\lambda_2\delta(\lambda_1 - \lambda_2) + \tau(\rho_2 + 2\beta_2\delta - \rho_1\delta + 2\rho_2\delta)))) \tag{A.53}$$

$$T_{54} = \tau\delta\Delta a_2^{\mathrm{DS}}(\gamma_1(\rho_2 + \rho_1\delta) - 2\gamma_2\rho_1 + S_c^D(2\beta_2\gamma_1\tau\rho_1\delta + \gamma_1\tau(\rho_2(\delta - 1) + \beta_2\delta)(\rho_2 - \rho_1\delta) + \gamma_2\tau\rho_1(\rho_2 - \delta(2\beta_2 + \rho_1 + \rho_2) + \rho_1\delta^2) - \delta(\lambda_1 - \lambda_2)(\gamma_2(\lambda_1(\rho_2 + \rho_1\delta) - 2\lambda_2\rho_1) + \gamma_1(2\delta\lambda_1(\beta_2 + \rho_2) - \lambda_2(\rho_2 + \rho_1\delta)))) + \beta_1(\gamma_2\tau(S_c^D\rho_2 - 2\Delta a_2^{\mathrm{DS}}\delta)) + \delta S_c^D(2\beta_2(\gamma_1 - \gamma_2)\tau + 2\gamma_2\lambda_2(\lambda_1 - \lambda_2) + 2\gamma_1\tau\rho_2 - \gamma_2\tau(\rho_1 + 2\rho_2))). \tag{A.54}$$

Appendix B. Two scenarios on government intervention only on green product

Table B.1. Two scenarios for the government intervention on green product.

Disruption mode	Members	Profit function of members
Scenario 1	Supplier	$\overline{\Pi}_s^{\mathrm{DE}^*}\left(\overline{\varphi}^{\mathrm{DE}^*}\right) = \mathrm{Max}\left(\sum_{i=1}^{2}\left(\overline{W}_i^{\mathrm{DE}} - \overline{C}_i^{\mathrm{DE}}\right)\overline{D}_i^{\mathrm{DE}} - h\frac{\left(\overline{\varphi}^{\mathrm{DE}^*}\right)^2}{2} - E_c^D\left(\overline{D}_T^{\mathrm{DE}} - Q_D^*\right)\right)$
	Manufacturer	$\overline{\Pi}_m^{\mathrm{DE}^*}\left(\overline{P}_1^{\mathrm{DE}^*}, \overline{P}_2^{\mathrm{DE}^*}, \overline{\theta}^{\mathrm{DE}^*}\right) = \mathrm{Max}\left(\left(\delta\overline{P}_1^{\mathrm{DE}^*} - (1-\delta)\overline{W}_1^{\mathrm{DE}}\right)\overline{D}_1^{\mathrm{DE}} + \left(\overline{P}_2^{\mathrm{DE}^*} - \overline{W}_2^{\mathrm{DE}}\right)\overline{D}_2^{\mathrm{DE}} - \sum_{i=1}^{2} A_i\overline{D}_i^{\mathrm{DE}} - (1-\delta)\tau\frac{\left(\overline{\theta}^{\mathrm{DE}^*}\right)^2}{2} - E_c^D\left(\overline{D}_T^{\mathrm{DE}} - Q_D^*\right)\right)$
	Government	$\overline{\Pi}_g^{\mathrm{DE}^*}(\delta) = \zeta_1\left[\left((1-\delta)\overline{P}_1^{\mathrm{DE}} - \delta\overline{W}_1^{\mathrm{DE}}\right)\overline{D}_1^{\mathrm{DE}} - \delta\tau\frac{\left(\overline{\theta}^{\mathrm{DE}}\right)^2}{2}\right] + \zeta_2\left[S'\overline{\theta}^{\mathrm{DE}}\overline{D}_1^{\mathrm{DE}}\right]$
Scenario 2	Supplier	$\overline{\Pi}_s^{\mathrm{DS}^*}\left(\overline{\varphi}^{\mathrm{DS}^*}\right) = \mathrm{Max}\left(\sum_{i=1}^{2}\left(\overline{W}_i^{\mathrm{DS}} - \overline{C}_i^{\mathrm{DS}}\right)\overline{D}_i^{\mathrm{DS}} - h\frac{\left(\overline{\varphi}^{\mathrm{DS}^*}\right)^2}{2} - S_c^D\left(Q_D^* - \overline{D}_T^{\mathrm{DS}}\right)\right)$
	Manufacturer	$\overline{\Pi}_m^{\mathrm{DS}^*}\left(\overline{P}_1^{\mathrm{DS}^*}, \overline{P}_2^{\mathrm{DS}^*}, \overline{\theta}^{\mathrm{DS}^*}\right) = \mathrm{Max}\left(\left(\delta\overline{P}_1^{\mathrm{DS}^*} - (1-\delta)\overline{W}_1^{\mathrm{DS}}\right)\overline{D}_1^{\mathrm{DS}} + \left(\overline{P}_2^{\mathrm{DS}^*} - \overline{W}_2^{\mathrm{DS}}\right)\overline{D}_2^{\mathrm{DS}} - \sum_{i=1}^{2} A_i\overline{D}_i^{\mathrm{DS}} - (1-\delta)\tau\frac{\left(\overline{\theta}^{\mathrm{DS}^*}\right)^2}{2} - S_c^D\left(Q_D^* - \overline{D}_T^{\mathrm{DS}}\right)\right)$
	Government	$\overline{\Pi}_g^{*}(\delta) = \zeta_1\left[\left((1-\delta)\overline{P}_1^{\mathrm{DS}^*} - \delta\overline{W}_1^{\mathrm{DS}}\right)\overline{D}_1^{\mathrm{DS}} - \delta\tau\frac{\left(\overline{\theta}^{\mathrm{DS}^*}\right)^2}{2}\right] + \zeta_2\left[S'\overline{\theta}^{\mathrm{DS}}\overline{D}_1^{\mathrm{DS}}\right]$

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Authors contribution

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Data availability statement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

[1] I. Arto, V. Andreoni and J.M.Rueda Cantuche, Global impacts of the automotive supply chain disruption following the Japanese earthquake of 2011. *Econ. Syst. Res.* **27** (2015) 306–323.

[2] A. Aslani and J. Heydari, Transshipment contract for coordination of a green dual-channel supply chain under channel disruption. *J. Cleaner Prod.* **223** (2019) 596–609.

[3] Autonews from wire, Opel, Renault Production Hit by Shortage of Japanese Parts. Accessed August 13, 2014. http://www.autonews.com/article/20110318/COPY01/303189860/opel-renault-production-hit-byshortage-of-japanese-parts (2011).

[4] Z. Basiri and J. Heydari, A mathematical model for green supply chain coordination with substitutable products. *J. Cleaner Prod.* **145** (2017) 232–249.

[5] J. Bian, X. Guo and K.W. Li, Decentralization or integration: distribution channel selection under environmental taxation. *Transp. Res. Part E: Logistics Transp. Rev.* **113** (2018) 170–193.

[6] S. Biller, L.M.A. Chan, D. Simchi-Levi and J. Swann, Dynamic pricing and the direct-to-customer model in the automotive industry. *J. Electron. Commer Res.* **5** (2005) 309–334.

[7] P. Chowdhury, S.K. Paul, S. Kaisar and M.A. Moktadir, COVID-19 pandemic related supply chain studies: a systematic review. *Transp. Res. Part E: Logistics Transp. Rev.* **148** (2021) 102271.

[8] A. Diabat, D. Kannan and K. Mathiyazhagan, Analysis of enablers for implementation of sustainable supply chain management – a textile case. *J. Cleaner Prod.* **83** (2014) 391–403.

[9] Z.P. Fan, S. Huang and X. Wang, The vertical cooperation and pricing strategies of electric vehicle supply chain under brand competition. *Comput. Ind. Eng.* **152** (2021) 106968.

[10] A. Fander and S. Yaghoubi, Impact of fuel-efficient technology on automotive and fuel supply chain under government intervention: a case study. *Appl. Math. Modell.* **97** (2021) 771–802.

[11] A. Fander and S. Yaghoubi, Dynamic and stochastic modeling for a closed-loop automotive supply chain under fuel issue and government intervention: a case study. *Comput. Ind. Eng.* **174** (2022) 108765.

[12] M. Frostenson and F. Prenkert, Sustainable supply chain management when focal firms are complex: a network perspective. *J. Cleaner Prod.* **107** (2015) 85–94.

[13] J. Gao, Z. Xiao and H. Wei, Competition and coordination in a dual-channel green supply chain with an eco-label policy. *Comput. Ind. Eng.* **153** (2021) 107057.

[14] A. Ghavamifar, A. Makui and A.A. Taleizadeh, Designing a resilient competitive supply chain network under disruption risks: a real-world application. *Transp. Res. Part E: Logistics Transp. Rev.* **115** (2018) 87–109.

[15] M.A. Gorji, M.B. Jamali and M. Iranpoor, A game-theoretic approach for decision analysis in end-of-life vehicle reverse supply chain regarding government subsidy. *Waste Manage.* **120** (2021) 734–747.

[16] T. Hadi, S.K. Chaharsooghi, M. Sheikhmohammady and A. Hafezalkotob, Pricing strategy for a green supply chain with hybrid production modes under government intervention. *J. Cleaner Prod.* **268** (2020) 121945.

[17] A. Hafezalkotob, Competition of two green and regular supply chains under environmental protection and revenue seeking policies of government. *Comput. Ind. Eng.* **82** (2015) 103–114.

[18] A. Hafezalkotob, Direct and indirect intervention schemas of government in the competition between green and non-green supply chains. *J. Cleaner Prod.* **170** (2018) 753–772.

[19] M. Heger and M. Sarraf, Air pollution in tehran: health costs, sources, and policies, in Environment and Natural Resources Global Practice Discussion Paper; No. 6. World Bank, Washington, DC (2018).

[20] S. Hosseini, D. Ivanov and A. Dolgui, Review of quantitative methods for supply chain resilience analysis. *Transp. Res. Part E: Logistics Transp. Rev.* **125** (2019) 285–307.

[21] D. Ivanov, Revealing interfaces of supply chain resilience and sustainability: a simulation study. *Int. J. Prod. Res.* **56** (2018) 3507–3523.

[22] D. Ivanov, A. Dolgui, B. Sokolov and M. Ivanova, Literature review on disruption recovery in the supply chain. *Int. J. Prod. Res.* **55** (2017) 6158–6174.

[23] S. Jun and S. Park, Examining technological competition between BMW and Hyundai in the Korean car market. *Technol. Anal. Strategic Manage.* **28** (2016) 156–175.

[24] E.S. Kasim, D. Daud, J. Said, N. Md Zin and E. Kusrini, Supply disruption risk mitigation: a case study of automotive company. *Polish J. Manage. Stud.* **22** (2020). DOI 10.17512/pjms.2020.22.1.16.
[25] P.R. Kleindorfer and G.H. Saad, Managing disruption risks in supply chains. *Prod. Oper. Manage.* **14** (2005) 53–68.
[26] S. Li and Y. He, Compensation and information disclosure strategies of a green supply chain under production disruption. *J. Cleaner Prod.* **281** (2021) 124851.
[27] C. Liu and W. Chen, Decision making in green supply chains under the impact of the stochastic and multiple-variable dependent reference point. *Transp. Res. Part E: Logistics Transp. Rev.* **128** (2019) 443–469.
[28] J. Ma, Y. Hou, Z. Wang and W. Yang, Pricing strategy and coordination of automobile manufacturers based on government intervention and carbon emission reduction. *Energy Policy* **148** (2021) 111919.
[29] H. Matsuo, Implications of the Tohoku earthquake for Toyota s coordination mechanism: supply chain disruption of automotive semiconductors. *Int. J. Prod. Econ.* **161** (2015) 217–227.
[30] C. Midler and C. Navarre, Project management in the automotive industry, in The Wiley Guide to Managing Projects. Wiley (2004) 1368–1388.
[31] E.U. Olugu, K.Y. Wong and A.M. Shaharoun, Development of key performance measures for the automobile green supply chain. *Res. Conserv. Recycl.* **55** (2011) 567–579.
[32] K. Rahmani and M. Yavari, Pricing policies for a dual-channel green supply chain under demand disruptions. *Comput. Ind. Eng.* **127** (2019) 493–510.
[33] M. Rasti-Barzoki and I. Moon, A game theoretic approach for car pricing and its energy efficiency level versus governmental sustainability goals by considering rebound effect: a case study of South Korea. *Appl. Energy* **271** (2020) 115196.
[34] J. Sarkis, Supply chain sustainability: learning from the COVID-19 pandemic. *Int. J. Oper. Prod. Manage.* **41** (2020) 63–73.
[35] D. Simchi-Levi, W. Schmidt, Y. Wei, P.Y. Zhang, K. Combs, Y. Ge, O. Gusikhin, M. Sanders and D. Zhang, Identifying risks and mitigating disruptions in the automotive supply chain. *Interfaces* **45** (2015) 375–390.
[36] R.M. Vanalle, W.C. Lucato, G.M.D. Ganga and A.G. Alves Filho, Risk management in the automotive supply chain: an exploratory study in Brazil. *Int. J. Prod. Res.* **58** (2020) 783–799.
[37] S. Xu, X. Zhang, L. Feng and W. Yang, Disruption risks in supply chain management: a literature review based on bibliometric analysis. *Int. J. Prod. Res.* **58** (2020) 3508–3526.
[38] M. Yavari and H. Zaker, Designing a resilient-green closed-loop supply chain network for perishable products by considering disruption in both supply chain and power networks. *Comput. Chem. Eng.* **134** (2020) 106680.
[39] YN, Agency, Hyundai develops new fuel-efficient engine technology. Accessed July 3, 2019. https://en.yna.co.kr/view/AEN20190703004800320 (2019).
[40] T. Zaefarian, M. Andabili, H. Momeni and S.E. Najafi, Iran auto market price segmentation and car ranking in segments using a hybrid DEMATEL-Two-Step clustering-TOPSIS approaches and two-step weighting based on Shannon's entropy. *Ind. Manage. Stud.* **16** (2018) 159–192.
[41] Y. Zhang and M. Hansen, Real-time intermodal substitution: strategy for airline recovery from schedule perturbation and for mitigation of airport congestion. *Transp. Res. Record* **2052** (2008) 90–99.
[42] X. Zhang and H.A.U. Yousaf, Green supply chain coordination considering government intervention, green investment, and customer green preferences in the petroleum industry. *J. Cleaner Prod.* **246** (2020) 118984.
[43] J. Zhang, X. Chen and C. Fang, Transmission of a supplier's disruption risk along the supply chain: a further investigation of the Chinese automotive industry. *Prod. Planning Control* **29** (2018) 773–789.
[44] J.H. Zhao, D.L. Zeng, L.P. Che, T.W. Zhou and J.Y. Hu, Research on the profit change of new energy vehicle closed-loop supply chain members based on government subsidies. *Environ. Technol. Innov.* **19** (2020) 100937.