Cooperation Mechanisms For A Competitive, Sustainable Food Supply Chain To Reduce Greenhouse Gas Emissions

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Cooperation mechanisms for a competitive, sustainable food supply chain to reduce greenhouse gas emissions

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Abstract

The food industry is one of the main emitters of greenhouse gases (GHG). The consumers of this industry are aware of the unpleasant consequences of GHG emissions such as global warming and climate change, so food supply chain members should consider mechanisms to reduce GHG emissions besides economic and social goals. This paper examines the impacts of the supply chain structure and cooperation methods on the goals and decisions of a sustainable food supply chain. The proposed supply chain consists of one manufacturer and two suppliers, competition, and cooperation between those studied with centralized and decentralized structures. A single-level problem is solved for the centralized supply chain in the first scenario. The decentralized structure is then considered for the other four scenarios, and bi-level programming is used to model competition and cooperation between the members. Computational results demonstrate that the maximum total profit of the supply chain among all the decentralized scenarios is obtained with the alliance of the manufacturer and the first supplier. It is found economical to increase the budget in the scenarios where the supply chain members competed with each other. Moreover, increasing production capacity and budget reduce GHG emissions for the supply chain members forming coalitions.

Keywords: Food supply chain; Greenhouse gas emission; Cooperation mechanisms; Competition; Game theory; Bi-level programming.

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33 **Ethics approval and consent to participate**

34 Not applicable.

35 **Consent for publication**

36 Not applicable.

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48

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1. Introduction

The increase in population has led to an increase in demand for food products, and there is no balance between the production and consumption of these products due to the lack of resources, so sustainability should be considered as an essential feature of the food supply chain (Martínez-Guido et al., 2018). The production of dairy products, one of the most important food products in any country's economy, leads to air pollution and waste of resources throughout the supply chain (Kirilova and Vaklieva-Bancheva, 2017). GHG emissions is one of the most tangible criteria for investigating the supply chain's environmental consequences, such as climate change and global warming. These environmental changes are harmful to man and other species, and customer awareness thereof has increased. There is greater demand for products that provide sustainability throughout the supply chain process from production to delivery to the customer. Supply chain members wish to increase demand and reduce costs by considering these issues, so all aspects of a sustainable supply chain must be considered in decision-making. Supply chain members have conflicting goals, and therefore they need to cooperate to improve their performance. Governments and related organizations are responsible for public health and must closely monitor all food supply chain processes.

Food product companies seek to maintain their competitive positions among customers by creating competitive advantages. Quality is one of the most important criteria for increasing the demand for food products besides sustainability issues. The supply chain members add additives to their products for various purposes, such as increasing demand and reducing costs. Excessive use of this type of additive may contaminate food and cause health problems for consumers. Song and Zhuang (2018) have mentioned too much melamine in dairy products by Sanlu Company in 2008, which led to kidney stones and several children's deaths. Consumer health has gained significance due to unfortunate events. Supply chain members seek to maximize their profits by abusing the lack of proper communication with the consumers, so the government and relevant organizations should monitor all the stages of the food supply chain (Song and Zhuang, 2017). Health protocols restrict the use of additives, and the government can also prevent members of the supply chain from overusing them by imposing fines.

One decision-maker makes decisions about the entire supply chain in a centralized one. In a decentralized supply chain, each member of the supply chain makes decisions based on their own goals, which may conflict with other members'. Game theory is used to model competition between decentralized supply chain members. Nash equilibrium is obtained in competition between two players with the same power (Tabrizi et al., 2018). The Stackelberg game is used where one player has more power than the others. First, the player with more power (leader) decides according to his goal and predicts the reaction of other players (followers), and the other players then react to the decision (Sharif et al., 2018). Bi-level programming is a combination of the Stackelberg game and mathematical planning, and decisions made at each level affect the other (Wang et al., 2017).

Supply chain members work together to improve their performance and the supply chain. Cooperation between supply chain members can be contractual or non-contractual. Alliance and shared supply chain members in costs and revenues are mechanisms of cooperation.

In this paper, a sustainable food supply chain consisting of one manufacturer and two suppliers is studied. The manufacturer seeks to increase demand by investing in the reduction of GHG emissions. The purpose of product additives is to increase demand and reduce costs. All three economic, environmental, and social dimensions of a sustainable supply chain are considered here. This paper aims to examine the impact of the supply chain structure and relationships between the members with respect to goals and decisions. Five scenarios are presented to compare the impacts of competition and cooperation between supply chain members on their goals and decisions in centralized and decentralized structures. A centralized supply chain is considered for the first scenario, and bi-level programming is used to model the competition between supply chain members in the other scenarios.

Given the above assumptions, we seek to answer these questions.

- 1) What are the effects of considering different supply chain structures on supply chain members' goals and decisions?
- 2) What is the impact of competition between supply chain members on their goals and decisions?
- 3) What are the effects of the three proposed cooperation scenarios between supply chain members on their goals and decisions?
- 4) What share of the cost of reducing GHG emission should the second supplier have for a better effect on the supply chain members' economic and environmental goals in the fourth and fifth scenarios?
- 5) What are the effects of the parameters concerning each of the economic, environmental, and social dimensions of the supply chain on its other dimensions?

The rest of the article is organized as follows. In the second section, the related articles are reviewed, and the research gap is identified. The problem is described, and the objective functions and constraints for each of the supply chain members are presented in the third section. Five scenarios are investigated in the fourth part of the described problem. The solution approach is explained in the fifth section. A mathematical analysis is presented in the sixth section to examine the impacts of several important parameters and compare the decisions made by the two suppliers. In the seventh section, numerical results are presented through the solution of an example problem with the five scenarios, and sensitivity analyses are made for several important parameters. The conclusions of the study and suggestions for future research are presented in the final section.

2. Literature review

The literature review consists of three subsections. In the first part, we review articles that have studied the competition and cooperation of green, sustainable supply chain members. The papers in the field of food supply chain are reviewed in the second part. The third part examines articles that use bi-level planning to model competition in the supply chain.

2.1. Competition and cooperation in the green, sustainable supply chain

In this section, articles in the field of competition and cooperation in the green, sustainable supply chain are reviewed. Zhou and Qin (2015) have reviewed papers on sustainable supply chain management based on game theory. The articles are reviewed in three respects: objective function, game type, and coordination. The authors conclude that a small number of articles have considered environmental and social objective functions besides the economic one, adopting multi-level models and studying the coordination mechanism along with competition. Raj et al. (2018) have investigated centralized and decentralized structures for a sustainable supply chain, including a supplier and a buyer. The Stackelberg game is used to model a decentralized supply chain. The supplier (leader) seeks to maximize its profit by determining the type of contract and green degree of the product. The buyer (follower) maximizes its profit by determining the amount of order and cooperation in the social dimension of the sustainable supply chain. Jian et al. (2019) have studied price competition between two firms in a duopoly market with different average carbon emissions per unit of homogenous products. Carbon emission regulation and cooperation mechanisms are proposed for comparison. Peng et al. (2019) have investigated the main reasons for environmental failure considering the behavioral game between government and manufacturing enterprises. Evolutionary game is used to model competition between them to implement extended producer responsibility (EPR) for e-waste. Simulation analysis is done with different strategies and improving relevant law and increasing inspection are introduced as methods to reduce environmental failures for government.

The above review shows that competition and cooperation in the sustainable supply chain have been considered in a small number of articles. Consumer health has not been considered as a social dimension of the sustainable supply chain in any of the articles. Nor has any of them considered competition and cooperation in a sustainable food supply chain.

Zhang et al. (2015) have investigated the competition and collaboration between a producer and a retailer in a product supply chain with a controllable decline rate. Decentralized and centralized scenarios are considered for the supply chain, where the producer is the leader of the Stackelberg game in the decentralized scenario. Cooperation between the retailer and the producer is considered through a revenue-sharing agreement, and the models are solved using a heuristic algorithm. Ji et al. (2017) have studied the reduction of carbon emissions in a supply chain, including a producer and a retailer. The Stackelberg game is used for modeling the decentralized

supply chain, in which the producer is the leader. It is assumed that the consumer is interested in buying products with less GHG emissions during the supply chain operation and that the producer invests in reducing GHG. Zhu and He (2017) have investigated the impacts of competition and cooperation on the green degree of products in a supply chain, including a manufacturer and a retailer. Centralized and decentralized structures are considered there for green product design. Competition between supply chain members is based on price and green degree. Hafezalkotob (2017) has studied competition and cooperation between two green supply chains, each including a manufacturer and a retailer, along with government intervention. The manufacturer determines the wholesale price of the product and the level of energy-saving to maximize profit. The retailer maximizes profit by setting the price of the product. The government seeks to guide the supply chain members toward economic and environmental goals by setting tariff rates. The notion of *coopetition* is presented for the first time in that paper, in which supply chain members work together to save energy and compete on pricing strategy. Xu et al. (2019) have studied a supply chain, including one producer and one retailer, to examine the impacts of various government tax policies on the supply chain members' decisions about carbon pricing and emissions. Government policies are defined in terms of the involvement of the supply chain members in the tax policy. The Stackelberg game is used to model competition between the government (leader) and supply chain members (followers) to achieve their goals. The goal of the supply chain members and the government is to maximize profit and sustainability, respectively. Sarkar and Bhadouriya (2020) have investigated competition and cooperation between members of the bi-level supply chain. Three models are presented for a supply chain, including a retailer and several manufacturers. The centralized supply chain is investigated for the first model for the maximization of total profit. The Stackelberg game is used to address the competition between the members in the second and third models. The retailer (leader) and manufacturers (followers) seek to maximize their profits by determining the quality of green and non-green products and retail prices, respectively. The manufacturers form a coalition in the third model, and Nash equilibrium is obtained for competition between manufacturers in the second model.

Most of the above articles have studied competition between companies at different levels. Competition between different companies at the same level of the supply chain has been investigated in a smaller number of studies. GHG emission reduction, product green degree, and energy level saving have been considered as environmental criteria in various articles. A small number of articles have considered competition over price and environmental criteria simultaneously.

2.2. Food supply chain

This section reviews articles with the topics of quality, sustainability, and competition in the food supply chain. Ahumada and Villalobos (2009) have reviewed articles in the food and agriculture supply chain and have concluded that health, risk management, and uncertainty were less studied.

Wang and Li (2012) have studied quality control in a milk supply chain, including a supplier and a retailer. Both members' goal is to maximize profit, and quality control is carried out in both parts of the supply chain. Centralized and decentralized structures are considered for the supply chain. In the decentralized supply chain, the Stackelberg game is used to model competition between the retailer (leader) and supplier (follower). Govindan et al. (2014) have presented a multi-objective model for locating and routing perishable food supply chains. Minimization of costs and carbon dioxide emissions are considered as objective functions for the problem. The presented model is multi-level and multi-vehicle. Kirilova and Vakkaliya-Bancheva (2017) have presented a bi-objective model for the green design of dairy products. The objective functions considered for the problem include the minimization of cost and GHG emission. The environmental objective function is converted into a cost objective function, and the model is solved with a single objective. Rohmer et al. (2019) have proposed a multi-objective model including cost and environmental objective functions for sustainable food supply chain network design. Various environmental dimensions, such as climate change and resource utilization, are considered for the environmental objective function. The multi-objective model is solved by the ε -constraint method with different criteria considered for the environmental objective function, and the results are compared. Li and Zhou (2021) have proposed a multi-objective model for a cold supply chain to improve customer satisfaction, reduce carbon emissions and minimizing costs. Dynamic and static carbon emission of supply chain is considered to determine environmental effects and a non-dominated genetic algorithm is presented to solve the proposed multi-objective model. Shirzadi et al. (2021) have proposed an inventory-routing model to optimize the total interest of agri-food reverse logistics by considering freshness quality and environmental effects. Collection and reuse of wasted products and controlling of GHG emission is considered as the environmental dimension of the green supply chain. Costs and qualities are assumed to be fuzzy, and the bipolar approach is used for fuzzy programming.

Researchers have paid more attention in recent years to the issues of quality and sustainability in the food supply chain. At most, two of the three sustainability dimensions have been investigated for the sustainable food supply chain. None of the available articles has considered all three economic, environmental, and social dimensions.

Song and Zhuang (2018) have studied the addition of additives and their health consequences in the milk supply chain. They assume that the manufacturer uses additives to increase demand, and the government prevents the overuse of these substances by imposing fines. Centralized and decentralized structures are considered for the supply chain, and the Stackelberg game is used to model competition between the government (leader) and the manufacturer (follower) to maximize profit. Song and Zhuang (2017) have proposed three models for the health issue in the milk supply chain. Centralized and decentralized structures are examined for the problem, including three players: the supplier, manufacturer, and government. In the first model, the centralized supply chain is considered to maximize the total profit of the supply chain. The decentralized structure is

provided for the second and third models. There are coalition and competition between the supplier and the manufacturer in the second and third models. In the second model, the Stackelberg game is used to model competition between the government (leader) and coalition (follower). In the third model, the government has the greatest power among the Stackelberg game players, and the manufacturer has more power than the supplier. Zhu et al. (2018) have investigated competition between food supply chain members on the green degree of products. Centralized and decentralized structures are considered for the supply chain, including a supplier and a producer. It is assumed that the green degree of a product depends on the green degrees of the raw materials needed to produce it. The producer and supplier compete on the green degrees of the products and raw materials to maximize profit. The cost-sharing mechanism is provided to improve the performance of the supply chain members. Yu and Cruz (2019) have studied the competition between firms aimed at maximizing profit. A network model is designed for an oligopolistic industry with different environmental policies. The effects of different tax policies, such as the flat emission tax rate on the goals and decisions of the companies, are examined, and the variable inequality method is used to solve the model. Manteghi et al. (2020) have presented three models for a sustainable food supply chain, including a manufacturer and two suppliers, to study the impact of cooperation and competition between supply chain members on sustainable aspects. Centralized structure is studied for the first model and competition and cooperation is investigated in the second and third models for a decentralized supply chain.

It is concluded from the above review that health in the food supply chain is a relatively new problem. Few articles have studied competition and cooperation for the food supply chain, and none has investigated the impact of relationships between supply chain members on achieving sustainability goals.

2.3. Bi-level programming

In this section, we review articles that have used bi-level programming to model their problems. Yue and You (2017) have investigated the competition between members of a biofuel supply chain using bi-level programming. A heuristic algorithm is presented for solving a mixed-integer bi-level model because of the discrete variable at the lower level (follower). Saranwong and Likasiri (2017) have presented a bi-level optimization model to minimize the cost of transferring products from factories to customers. The goal of the upper level is to minimize fixed costs and the cost of transferring products from manufacturers to distributors. The goal of the lower level is to minimize the cost of transferring products from distribution centers to customers. Four algorithms are considered for solving the bi-level model, the results obtained by which are compared to each other. Golpîra et al. (2017) have presented a bi-level programming model to design a green supply chain. The goal of the upper level is to minimize the total cost of the supply chain, and the lower level is aimed at minimizing the risk of uncertainty for retailers. The KKT approach is used to convert the bi-level model to a one-level one. Wang et al. (2017) have presented a bi-level model

for a supply chain with the goal of reducing carbon emissions. Two scenarios are defined for the problem, one of which includes more buyer power than seller power, while the other includes the opposite power distribution. A modified evolutionary algorithm is presented to solve the bi-level model because of the discrete variables at the lower level. Tabrizi et al. (2018) have studied the competition between the fish supply chain members by presenting a bi-level model. The supply chain includes several suppliers and sales centers, and there is competition between them to maximize profit. Bi-level programming is used to model the competition in which suppliers (upper level) have more power than sales centers (lower level). The suppliers and the sales centers compete with each other at the same level. Nash equilibrium is obtained for the optimal value of supply and inventory policy for the upper level and the inventory of the sales center for the lower level. The particle swarm optimization (PSO) algorithm is used to solve the problem. Safaei et al. (2018) have presented a robust bi-level optimization model for the relief supply chain. The transshipment relief points constitute the upper level of the model to minimize costs. Risk minimization is the goal of the supplier relief points, making up the lower level of the model. The scenario-based approach is used to consider uncertainty. The bi-level model is converted to a single-level model using the KKT conditions. Sharif et al. (2018) have presented a multi-product bi-level model to maximize the profits of the municipality and buyers. The municipality decides on network design, pricing, outsourcing, bidding, and company selection to maximize its profits at the upper level. The buyers determine price at the lower level to maximize their profits. A heuristic approach is presented to solve the mixed-integer bi-level model, the results of which are compared to those of the KKT method. In most research, there is a single decision-maker for the upper and lower levels of bi-level programming.

2.4. Research gap

According to the above review, health is a new issue for the food supply chain. Additives and GHG emissions are both harmful to consumer health, and none of the researchers has investigated them as social and environmental criteria for a sustainable supply chain. Nor has any of them considered all the three economic, environmental, and social dimensions for such a supply chain. According to Table (1), centralized and decentralized structures have been studied for the supply chains in most articles to enable comparison. Competition between supply chain members at the same level has been studied in a few of them. Comparing different scenarios of cooperation, such as alliance and cost-sharing, is useful for providing management suggestions. A few researchers have considered cooperation as a mechanism for improving the performance of supply chain members besides the competition. Manteghi et al. (2020) have investigated the impacts of supply chain structure and competition and cooperation between members in achieving the goals of a sustainable food supply chain. They have used game theory to model competition between supply chain members, and the alliance is considered a cooperation mechanism in this paper. The use of additives and emissions should be limited in practice, and bi-level programming is used to model

competition between supply chain members. Bi-level programming combines the Stackelberg game and mathematical modeling, and few of the papers have used it for the above purpose.

This paper studies the competition and cooperation between members of a dairy supply chain, including one manufacturer and two suppliers. The reduction of GHG emissions and the use of additives are considered as competitive advantages, and prices can increase the demand for food products, thereby playing an important role in public health and achievement of the economic goals of the supply chain members. All three economic, environmental, and social dimensions of the supply chain must be considered to improve the members' performance in the long term. Five scenarios are considered in this paper to compare the impacts of competition and cooperation between supply chain members on their goals and decisions. A single-level model is presented for a centralized supply chain in the first scenario. Bi-level programming is used in other scenarios to model competition between members of a decentralized supply chain. Alliance and cost-sharing are considered as mechanisms for cooperation between members of the supply chain in the third to fifth scenarios.

Table (1) Comparison of the major papers mentioned in the literature review

	Structure		Sustainability		Competition		Cooperation		Modeling	
	Centralized	Decentralized	Economical	Environmental	Social	Nash	Stackelberg		Game Theory	Mathematical Programming
Ji et al. (2017)		*	*	*			*		*	
Golpîra et al. (2017)		*	*	*			*		*	*
Song and Zhuang (2017)	*	*	*		*		*	*	*	
Song and Zhuang (2018)	*	*	*		*		*		*	
Sharif et al. (2018)		*	*	*			*		*	*
Zhu et al. (2018)	*	*	*	*			*	*	*	
Tabrizi et al. (2018)		*	*			*	*		*	*
Raj et al. (2018)	*	*	*	*	*		*	*	*	
Rohmer et al. (2019)		*	*	*						*
Sarkar and Bhadouriya (2020)	*	*	*	*			*	*	*	
Manteghi et al. (2020)	*	*	*	*	*		*	*	*	
Current research	*	*	*	*	*	*	*	*	*	*

3. Problem definition

The manufacture of products emits GHG, and the negative impacts of GHG emissions on the environment and health of living organisms are evident. The manufacturer increases its costs by investing in the reduction of GHG emissions. Additives are added to products by the manufacturer for purposes such as increasing revenue and reducing costs. Excessive use of additives may be harmful to consumers' health, so supply chain members or external inspectors should control the process. The government can also impose fines to prevent the overuse of substances. The reduction of GHG and the use of additives affect public health, environmental goals, and supply chain member profits, so decisions about them must be made simultaneously.

Figure (1) Centralized (a) and decentralized (b, c, d) proposed scenarios

This paper investigates a bi-level supply chain of dairy products, including one manufacturer and two suppliers. In the examined problem, the manufacturer aims to maximize profit by determining the reduction of GHG emissions and the percentage of additives as well as prices. The suppliers compete with each other to maximize their profits by setting the prices of raw materials. Centralized and decentralized structures are considered for the problem, the impacts of which on the goals and variables of the problem are investigated. The centralized supply chain is considered in the first scenario, and the structures in the other four scenarios are decentralized. In the second scenario, there is competition between members of the supply chain to maximize profit. Cooperation between supply chain members is considered besides the competition in the third to

fifth scenarios. In the third scenario, an alliance is formed between the manufacturer and the first supplier. The second supplier cooperates with the manufacturer in the fourth scenario by sharing the cost of reducing GHG emissions with the first supplier. In the fifth scenario, the first supplier allies with the manufacturer, and the second cooperates with it to decrease the cost of reducing GHG emissions. A schematic of the five scenarios is shown in Figure 1. Bi-level programming is used in the second to fifth scenarios to model competition and cooperation between the manufacturer and suppliers.

In this paper, the manufacturer produces two substitutable products with a share of the market demand of μ_i . The value of the customer demand function for each product depends on its price, and the product demand decreases by α for each unit of increase in the product price. The products are substitutable, so the demand for each increases by δ , increasing the price of each unit of the other product. The demand for each product is a function of the percentage of additives and reduced GHG emissions besides the price. An increase in the percentage of additives improves the appearance of the product and increases its demand. Customers are environmentally conscious; therefore, the demand for products with lower GHG emissions is higher. The demand function is presented in Relation (1), common in the research literature (Ji et al., 2017; Zhu et al., 2018). One unit of raw materials is required for the manufacture of each unit of product, and Supplier 1 and Supplier 2 are responsible for the preparation of the raw materials for production of the first and second products, respectively, so the index i is used only for the product. The symbols in Relation (1) are described in the Definition of Symbols section.

$$d_i = \mu_i \bar{d} - \alpha p_i + \delta p_{3-i} + \beta x + \gamma \Delta \quad , \quad \forall i \quad (1)$$

Index

i : Product ($i = 1,2$)

Parameters

g : Government penalty for endangerment of consumer health

f : Cost of using one percent additive in one unit of milk (1 kg)

m : Cost of using one percent protein in one unit of milk (1 kg)

s_i : Supplier capacity of raw materials for product i

u : Maximum allowable additives used in one unit of product

ϕ : Density of nitrogen in one percent of the additive

o : Density of nitrogen in one percent of protein

n : Minimum amount of nitrogen required in the product

373 ρ : Second supplier's share of the cost of reduction of GHG emission
 374 θ : Slope for the probability of endangering consumer health
 375 r : Cost of one-unit reduction of GHG emission
 376 τ : Capacity of the manufacturer
 377 σ_i : Cost of manufacture of one unit of product i
 378 c_i : Cost of supply of raw materials for the manufacture of one unit of product i
 379 k : Cost of one unit of reduction of GHG emission
 380 B : Budget of the manufacturer
 381 E : Maximum allowable GHG emissions
 382 $\bar{d}$: Market base of the product
 383 α : Self-price sensitivity coefficient of demand
 384 δ : Cross-price sensitivity coefficient of demand
 385 β :Demand sensitivity to one unit of reduction of GHG emission
 386 γ :Demand sensitivity to one percent of the additive
 387 e : Volume of GHG emitted through the manufacture of one unit of product
 388 μ_i : Market-based share of product i
 389 **Variables**
 390 p_i : Price of product i
 391 v_i : Margin profit of product i
 392 x : Reduction of GHG emission
 393 w_i : Wholesale price of raw materials used in one unit of product i
 394 Δ : Percentage of additive in one unit of product
 395 l : Percentage of protein in one unit of product
 396 **Function**
 397 H : Probability of endangering consumer health
 398 d_i : Demand function of product i

In this problem, the goal of each supply chain member is to maximize its profit, which results from the difference between income and costs. Manufacturer costs include production costs, the cost of investment in clean technologies to reduce GHG emissions, and the cost of purchasing raw materials from the suppliers. It is assumed that the manufacturer produces dairy products, and the cost of using protein in these products is ml . The manufacturer uses melamine instead of protein to reduce costs and increase demand, and the cost of using melamine is $f\Delta$. According to the protocols, the percentage of melamine used should not exceed a certain amount, which is considered a constraint in the problem. Excessive use of melamine causes health problems for consumers, so the government prohibits its overuse by imposing gH of fines to the manufacturer. The production process emits GHG at a social cost of $k(e - x)$. The demand for products with lower GHG emissions is higher, as mentioned in the previous section, so the manufacturer seeks to invest in modern, useful technologies to reduce GHG emissions. The reduction requires long-term investment, costing rx^2 according to related articles. Governments and private organizations adopt strict rules on maximum GHG emissions, regarded as a constraint in the model. The manufacturer also has a budget limit to pay for fines incurred due to the use of additives, GHG emission, and purchase of raw materials.

The suppliers seek to maximize their profits by setting initial prices for raw materials, directly impacting the prices of and the demand for the products, and the raw materials needed to manufacture a product increase as product demand rises. Each supplier is responsible for supplying one of the products. Strictly, the first and second suppliers are in charge of supplying the raw materials needed to manufacture the first and second products, respectively, and capacity limitations are involved in supplying raw materials. The mathematical models for the manufacturer and the suppliers are presented in the following sections.

Manufacturer model

$$\max Z_m = \sum_i d_i(p_i - w_i - \sigma_i - k(e - x) - ml - f\Delta - gH) - rx^2 \quad (2)$$

$$p_i = w_i + v_i, \quad \forall i \quad (3)$$

$$\phi\Delta + ol \geq n \quad (4)$$

$$H = \theta\Delta \quad (5)$$

$$\Delta \leq u \quad (6)$$

$$\sum_i d_i \leq \tau \quad (7)$$

$$x \leq e \quad (8)$$

$$\sum_i (e - x) d_i \leq E$$

(9)

$$\sum_i w_i d_i + \sum_i +gHd_i + rx^2 \leq B \quad (10)$$

$$p_i, v_i, x, \Delta, l \geq 0 \quad (11)$$

Relation (2) defines the objective function of the manufacturer. Product price is the sum of the profit margins considered by the manufacturer and the price of the raw materials, presented in Relation (3). Products are tested for quality throughout the process, where they must exhibit a minimum amount of protein. The percentage of nitrogen in a dairy product is measured to determine the amount of protein. In this paper, it is assumed that the manufacturer uses additives instead of protein to reduce costs. Each unit of dairy product must contain the minimum amount of nitrogen, presented in Relation (4). Consumption of additives may be detrimental to consumer health, and the government is assumed to impose fines on the endangerment of consumer health. The health probability function represents the social dimension of the problem, which depends on the percentage of additives used (Song and Zhuang, 2017, 2018). The probability function of health risk is linearly dependent on the percentage of additives in the problem, as presented in Relation (5). It is not enough to consider a fine on additives, the amount of which should not exceed the set limit, indicated by Relation (6). Relation (7) shows the limit on manufacturer capacity for both types of products. Relation (8) indicates that the maximum reduction of GHG emissions is as much as the amount of emission from the manufacture. Relations (9) and (10) determine budget constraints and maximum GHG emissions. The type of manufacturer variable is specified in Relation (11).

Supplier model

$$\max Z_{S_i} = w_i - c_i)d_i \quad (12)$$

$$d_i \leq s_i, \quad \forall i \quad (13)$$

$$w_i \geq 0, \quad \forall i \quad (14)$$

Relation (12) defines the objective function of each supplier. The amount of raw materials supplied by each supplier is limited, and Relation (13) specifies the maximum capacity of each supplier. Relation (14) identifies the type of variable of each supplier.

4. Competition and cooperation

In this section, the relationships between the supply chain members are studied in five scenarios. In the first scenario, the supply chain is assumed to be centralized, and a decision-maker decides about the entire supply chain to maximize total profit. It is assumed that each supply chain member decides to maximize its profit in the second scenario. This scenario investigates vertical competition between the manufacturer and the suppliers and horizontal competition between the

suppliers. The first supplier forms an alliance with the manufacturer in the third scenario to improve the supply chain goals in manufacturing the first product. The second supplier's share of reducing GHG emissions is considered a mechanism of cooperation in the fourth model besides competition between the supply chain members. In the fifth scenario, both suppliers cooperate with the manufacturer. The first supplier forms an alliance with the manufacturer, and the second one shares the cost of reducing GHG emissions. The above scenarios are considered to investigate the effect of the supply chain structure and the type of relationship between the chain members on the goals and decisions. Centralized and decentralized scenarios are presented for the problem and lemmas for solving the second to fifth scenarios.

4.1 Cooperation

In the first scenario, it is assumed that a single decision-maker decides about the entire supply chain. This scenario is considered an ideal case compared to the others and is less common in practice. The decision-maker aims to maximize the total profit of the supply chain by determining product prices, the percentage of melamine, the percentage of protein, and the reduction of GHG emissions. The objective function in this scenario is the sum of those of the supply chain members, as presented in Relation (15).

$$\max Z_c = Z_m + \sum_i Z_{s_i} = \sum_i d_i(p_i - c_i - \sigma_i - k(e - x) - ml - f\Delta - gH) - rx^2 \quad (15)$$

Subject to (4,5,6,7,8,9,10,11,13,14)

The decision-maker in the centralized model does not need to determine the price of raw materials and profit margins, so Relation (3) does not apply to this model. In this scenario, the relationships between the supply chain members are not considered, and the proposed model is single-level. The solution of a single-level model does not involve the complexities of solving a bi-level model. It is appropriate to consider a centralized supply chain for economic purposes (supply chain profit). Still, it is necessary to study the effect of a centralized structure on the environmental and social dimensions of a sustainable supply chain.

4.2. Decentralized competition

According to Relations (2) and (12), the suppliers' income is considered a cost incurred by the manufacturer, so the manufacturer seeks to supply the raw materials at the lowest price. In this scenario, there is competition (vertical) between the manufacturer and suppliers to maximize profit. The manufacturer seeks to maximize its profit by determining the profit margin, percentage of additives, percentage of protein, and reduction of GHG emissions. Each supplier is responsible for supplying the necessary raw materials for one type of product, and the price of the raw materials supplied by the suppliers affects the demand for the product according to Relations (1) and (3).

According to Relation (7), production capacity is limited, so there is a competition between the suppliers to maximize profit. Nash equilibrium is obtained for the competition between the suppliers. Bi-level programming is used for considering the competition between the manufacturer (leader) and the suppliers (followers), as presented below.

$$\max Z_m = \sum_i d_i(p_i - w_i - \sigma_i - k(e - x) - ml - f\Delta - gH) - rx^2 \quad (2)$$

Subject to (3,4,5,6,7,8,9,10,11)

$$\max Z_{S_i} = (w_i - c_i)d_i \quad (i = 1,2) \quad (12)$$

Subject to (13,14)

The existence and uniqueness of the Nash equilibrium obtained for the suppliers must be proven. First, lemma (1) is used to demonstrate that the Nash equilibrium between the two suppliers obtains at least one solution, and the uniqueness of the Nash equilibrium is then proven in lemma (2).

Lemma 1: The game between the suppliers to determine wholesale price involves at least one Nash equilibrium.

Lemma 2: The game between the suppliers to determine wholesale price involves exactly one Nash equilibrium.

Proofs for lemmas (1) and (2) are presented in Appendices (1) and (2), respectively.

4.3. Alliance between the manufacturer and the first supplier

In this scenario, it is assumed that the manufacturer allies with the first supplier. The alliance seeks to maximize the profits of the coalition members by determining the price of the first product, profit margin of the second product, percentage of additives, percentage of protein, and reduction of GHG emissions. The second supplier competes with the coalition by setting the wholesale price of the raw materials of the second product to maximize its profit. Bi-level programming is used to model the competition between the alliance (leader) and the second supplier (follower). The first supplier is responsible for providing the first product's raw materials, so the coalition can increase its demand by setting a lower price for the first product. The second supplier seeks to increase the price of raw materials for the second product due to the competition with the coalition members, which leads to a decrease in demand for the second product. The alliance's profit is presented in Relation (16), and Relation (3) in the third scenario is considered only for the second product. The bi-level programming model of the third scenario is presented below.

$$\begin{aligned} \max Z_{Co} &= Z_m + Z_{S_1} \\ &= d_1(p_1 - c_1 - \sigma_1 - k(e - x) - ml - f\Delta - gH) \\ &\quad + d_2(p_2 - w_2 - \sigma_2 - k(e - x) - ml - f\Delta - gH) - rx^2 \end{aligned} \quad (16)$$

Subject to (3,4,5,6,7,8,9,10,11,13,14)

$$\begin{aligned} \max Z_{S_2} &= (w_2 - c_2) d_2 \\ \text{Subject to} & \text{ (13,14)} \end{aligned} \quad (12)$$

4.4. Decentralized competition scenario with the cost-sharing mechanism

There is competition in this scenario between the manufacturer (leader) and the suppliers (followers) to maximize profit, as in the second scenario. The manufacturer seeks to maximize its profit by determining the product price, percentage of additives, percentage of protein, and reduction of GHG emission. The suppliers compete with each other by setting raw material prices to maximize profit. In this scenario, cooperation between the second supplier and the manufacturer is assumed to reduce GHG emissions costs. The manufacturer can reduce GHG emissions by helping the second supplier with the cost of reducing GHG emissions. Customer demand increases with the reduction of GHG emissions. The manufacturer's objective function is presented in Relation (17). In this model, it is assumed that the second supplier contributes to reducing GHG emissions with a share of ρ , and the objective functions of the first and second suppliers are presented in Relations (12) and (18). The second supplier should consider an increase in demand and prevent a sharp decline in the suppliers' profits from determining its share of reduction of GHG emissions. The second supplier's share of the cost of reducing GHG emission is very important in this model in the provision of a balance between economic and environmental goals. The bi-level programming model of the fourth scenario is presented below.

$$\max Z_m = \sum_i d_i (p_i - w_i - \sigma_i - k(e - x) - ml - f\Delta - gH) - (1 - \rho)rx^2 \quad (17)$$

$$\text{Subject to} \quad (3,4,5,6,7,8,9,10,11)$$

$$\max Z_{S_1} = (w_1 - c_1)d_1 \quad (12)$$

$$\text{Subject to} \quad (13,14)$$

$$\max Z_{S_2} = (w_2 - c_2)d_2 - \rho r x^2 \quad (18)$$

$$\text{Subject to} \quad (13,14)$$

Lemma (3) proves that the Nash equilibrium between the suppliers provides at least one answer for the fourth scenario. The uniqueness of that solution in the fourth model is proven in lemma (4).

Lemma 3: The game between the suppliers in the fourth scenario has at least one Nash equilibrium.

Lemma 4: The game between the suppliers in the fourth scenario has exactly one Nash equilibrium.

Proofs for lemmas (3) and (4) are presented in Appendices (3) and (4), respectively.

4.5. Alliance with the first supplier and cooperation mechanism for the second

In this scenario, the first supplier forms an alliance with the manufacturer, and the second supplier shares the cost of reducing GHG emissions. The coalition members compete with the second supplier, and their goal is to maximize the profit of the coalition by determining the price of the first product, profit margin of the second product, percentage of melamine, percentage of protein, and reduction of GHG emission. The second supplier's goal is to maximize its profit by setting the wholesale price of the raw materials of the second product. There are two types of mechanisms for cooperation in this scenario. The manufacturer seeks to reduce the price of and increase the first product demand by allying with the first supplier, as in the third scenario. In the second mechanism, the second supplier shares the cost of reducing GHG emissions by the manufacturer to increase the demand for the products and reduce GHG emissions, as in the fourth scenario. The coalition's profits and the second supplier are presented in Relations (19) and (20), respectively. Relation (3) is considered in the fifth scenario only for the second product, and the bi-level programming model of the scenario is presented below.

$$\max Z_{co} = Z_m + Z_{S_1} = d_1(p_1 - c_1 - \sigma_1 - k(e - x) - ml - f\Delta - gH) + d_2(p_2 - w_2 - \sigma_2 - k(e - x) - ml - f\Delta - gH) - (1 - \rho)rx^2 \quad (19)$$

Subject to (3,4,5,6,7,8,9,10,11,13,14)

$$\max Z_{S_2} = (w_2 - c_2) d_2 - \rho r x^2 \quad (20)$$

Subject to (13,14)

5. Mathematical analysis

The suppliers affect the manufacturer's decisions and goals and the supply chain by determining the wholesale price of the raw materials. This section assumes that the suppliers have sufficient capacity to supply raw materials for the products, and Relation (13) is not considered. The effects of the self-price and cross-price sensitivity coefficients of demand on the wholesale price of raw materials, product demand, and the suppliers' profits are investigated first for the second to fourth scenarios. Then, the raw material prices, demand, and prices of the first and second products in the second to fifth scenarios are compared.

Proposition 1: In the second and fourth scenarios,

$$1) \frac{\partial w_1}{\partial \alpha} \leq 0, \frac{\partial w_2}{\partial \alpha} \leq 0.$$

$$2) \frac{\partial Z_{S_1}}{\partial \alpha} \leq 0, \frac{\partial Z_{S_2}}{\partial \alpha} \leq 0.$$

$$3) \frac{\partial w_1}{\partial \delta} \geq 0, \frac{\partial w_2}{\partial \delta} \geq 0.$$

$$4) \frac{\partial Z_{S_1}}{\partial \delta} \geq 0, \frac{\partial Z_{S_2}}{\partial \delta} \geq 0.$$

A proof for proposition (1) is presented in Appendix (5).

The manufacturer seeks to reduce the product price by increasing the dependence of demand on the price to prevent a sharp decline in the demand for the products. The suppliers try to avoid a sharp drop in profit due to the decrease in demand by lowering raw material prices. The suppliers' profits also decrease as the prices of their raw materials decrease. The suppliers can prevent a drop in product demand and profit by contributing to other production costs, such as government fines for using melamine and the cost of reducing GHG emissions. Competition over price increases with the increasing dependence of product demand on the price of the other product. The manufacturer can increase the prices of its products without reducing demand by increasing competitiveness. The suppliers can also increase the price of raw materials by increasing their products' prices, and their profits also increase with an increase in the price of raw materials. They can increase their profits by setting high prices for raw materials where price competitiveness is high. It is concluded that the suppliers' knowledge of the product market is necessary for determining the appropriate pricing strategy.

Proposition 2: In the second and fourth scenarios,

1) If $\frac{\bar{d}(\mu_2 - \mu_1) + \alpha(c_2 - c_1)}{\alpha + \delta} \geq v_2 - v_1$ then $w_2 \geq w_1$; otherwise $w_2 < w_1$.

2) If $\frac{\bar{d}(\mu_2 - \mu_1)}{\alpha + \delta} + c_1 - c_2 \geq v_2 - v_1$ then $d_2 \geq d_1$; otherwise $d_2 < d_1$.

A proof for proposition (2) is presented in Appendix (6).

The demand for each product increases with the reduction of its profit margin concerning that of the other product. The price of raw materials increases with an increase in demand. The manufacturer must consider the impact of the decision on the product market and the goals of the other members of the supply chain before determining the profit margins for their products. The demand for each product increases with an increasing market share, and the suppliers can increase the prices of their raw materials by increasing demand. An increase in the cost of supply increases the price of raw materials, and the demand for the products decreases with an increase in their prices. The suppliers' profits increase with increases in the shares of the products and decreases in the costs of supply. Product type is very important in the manufacturer's and suppliers' specifications of the pricing strategy. Competition on pricing increases with the increasing dependence of price demand, so the manufacturer cannot sell a product with a high price difference to avoid a sharp drop in demand. The dairy market is always changing for reasons such as the arrival of new products and changing customer tastes, so companies can compete in the market to make the right decisions in the shortest times.

Proposition 3: In the third and fifth scenarios,

1) $\frac{\partial w_2}{\partial \alpha} \leq 0, \frac{\partial Z_{S_2}}{\partial \alpha} \leq 0$.

591 2) $\frac{\partial w_2}{\partial \delta} \geq 0, \frac{\partial Z_{S_2}}{\partial \delta} \geq 0.$

592 A proof for proposition (3) is presented in Appendix (7).

593 In the third and fifth scenarios, the manufacturer and first supplier form an alliance with each other
 594 and seek to maximize their demand and profits by reducing the price of the first product. As in
 595 proposition (1), the coalition members seek to reduce the product prices to prevent a sharp drop in
 596 demand by increasing its dependence on price. The second supplier also reduces the price of its
 597 raw materials to avoid a sharp decline in profit, increasing the dependence of demand on the
 598 product prices. The second supplier's profit decreases with a reduction in the price of raw materials.
 599 Product price competitiveness increases with an increase in the dependence of product demand on
 600 the price of the other product. The second supplier seeks to increase the product price by increasing
 601 competitiveness, leading to an increase in the price of raw materials and the profit of the second
 602 supplier. The coalition members seek to reduce the price of the first product to increase the demand
 603 for it and their profits, and it is not possible to drastically reduce the price of the first product by
 604 increasing competitiveness. The price difference between the products decreases with increasing
 605 competitiveness. In the third scenario, the second supplier can share the cost of reducing GHG
 606 emissions to increase the demand for the second product, as in the fifth scenario, and more raw
 607 materials are therefore needed. In the fifth scenario, the cost of reducing GHG emissions and the
 608 second supplier's share thereof are important.

609 **Proposition 4:** In the third and fifth scenarios,

610 1) If $p_1(2\alpha - \delta) - \alpha v_2 \geq \mu_2 \bar{d} + \beta x + \gamma \Delta + \alpha c_2$ then $p_1 \geq p_2$; otherwise $p_1 < p_2$.

611 2) If $p_1(2\alpha - \delta)(\alpha + \delta) - \alpha(\alpha - \delta)v_2 \geq \epsilon$ then $d_2 \geq d_1$; otherwise $d_2 < d_1$.

612 Where $\epsilon = \alpha^2 c_2 + (\alpha + \delta)(\beta x + \gamma \Delta) + \bar{d}(2\mu_1 \alpha + \mu_2(\alpha - \delta))$.

613 A proof for proposition (4) is presented in Appendix (8).

614 The alliance between the producer and the first supplier would be expected to reduce the price of
 615 the first product, which is higher than the price of the second product, however, under the
 616 conditions mentioned above. The price difference between the two products would decrease with
 617 a reduction of the second product's share of the market and lower effects of emissions and
 618 melamine on demand. A reduction of the price difference between the products leads to decreases
 619 in the demand for the first product and the coalition members' profits, so the coalition must decide
 620 with knowledge of market conditions and product type. It seems unlikely that the demand for the
 621 second product will be higher than that of the first product according to obtained results.

6. Solution method

Competition between the supply chain members is considered in the second to fifth scenarios assumed for the problem. The Nash game between the suppliers has a unique answer, given lemmas (2) and (4). Bi-level programming is used to model the competition between the manufacturer (leader) and the suppliers (followers) in the second and fourth scenarios. It is also used to compete between the alliance (leader) and the second supplier (follower) in the third and fifth scenarios. The KKT approach is used to solve the bi-level models, where KKT conditions are set for suppliers and added to the upper-level solution space to convert the bi-level models to single-level ones. According to Relations (13) and (14), the solution space of the suppliers is convex in the second to fifth scenarios. In the second to fifth scenarios, the second derivative of the objective function of each supplier with respect to the wholesale price of its raw materials ($\frac{\partial^2 Z_{S_i}}{\partial w_{it}^2} = -2\alpha$) is negative, so the objective functions are concave. The objective functions of the suppliers are concave in the second to fifth scenarios, so sufficient KKT conditions are met. The optimal values for the variables can be obtained through the KKT conditions if one of the constraint qualifications is met (Kuhn, 2006).

Lemma 5: Slater's quality condition is met for the second to fifth scenarios.

A proof for lemma (5) appears in Appendix (9).

The KKT conditions for each supplier are set as follows. First, the L_i function is formed for each supplier, as presented in Relation (21). The first KKT condition is obtained as the first derivative of the function concerning the variable for each supplier ($\frac{\partial L_i}{\partial w_i}$), and is set to zero in Relation (22). The complementary slackness condition is also considered for each objective function, as shown in Relation (23).

$$L_i = Z_{S_i} - \lambda_i (d_i - s_i) \quad , \quad \forall i \quad (21)$$

$$\mu_i \bar{d} + \beta x + \gamma \Delta + \alpha(c_i + \lambda_i - v_i - 2w_i) + \delta (v_{3-i} + w_{3-i}) = 0 \quad , \quad \forall i \quad (22)$$

$$\lambda_i(d_i - s_i) = 0 \quad , \quad \forall i \quad (23)$$

Relations (22) and (23) are considered for each supplier and added to the upper-level constraints to convert the bi-level models to single-level ones in the second to fifth scenarios. The objective functions for the scenarios are nonlinear, and so are some of their constraints.

7. Numerical results

In this section, a numerical example of a real case is considered to investigate the practical applications of the scenarios presented in the previous section. The information provided in this section is taken from Song and Zhuang (2018). The dairy supply chain is considered in this paper,

where quality control is very important for the products. The percentage of protein in each product is measured for that purpose. The density of nitrogen in the protein is 16%, and the amount of nitrogen in one kilogram of the dairy product is measured to determine its protein amount, which must be at least .0228. The cost of using protein is $.84 \frac{\text{RMB}}{\text{kg}}$. The density of nitrogen in melamine is .666, which is higher than that in protein, and the cost of using melamine is $.7 \frac{\text{RMB}}{\text{kg}}$, which is lower than the cost of using protein. The manufacturer uses melamine instead of protein to reduce costs and increase demand, but excessive melamine use causes health problems. In this paper, it is assumed that the probability of endangering health is linearly dependent on the percentage of melamine, and θ is estimated to be 106.3. The government has imposed a fine of 1,500 to prevent the manufacturer from using too much melamine, the maximum allowable amount of which to be used in the products is .0001. The carbon dioxide emission from the production of each unit of a dairy product is $1214 \frac{dc^3Co2}{kg}$ (Food and Organization, 2010). The social cost of GHG emissions is $.0007 \frac{\text{RMB}}{dc^3Co2}$ (Gillingham and Stock, 2018), and the manufacturer seeks to reduce GHG emissions to increase demand. The values of the other parameters are estimated according to experts' opinions and the values obtained from the previous articles. The first scenario involves a single-level model, and the others turn into single-level models using KKT conditions. The objective function is nonlinear in all the scenarios, as are some of the constraints. All the scenarios are solved in the GAMS software with the BARON solver.

The impacts of the different scenarios on the supply chain members' decisions and different goals of a sustainable supply chain are studied in Section 7.1. The second supplier shares the cost of reducing GHG emissions in the fourth and fifth scenarios. The effect on the goals and decisions of the supply chain members is examined in Section 7.2. The impacts of four parameters, including the total budget, manufacturer's capacity, government penalty for endangerment of consumer health, and cost of reduction of GHG emission, on the goals and decisions of the supply chain members, are investigated in Sections 7.3 to 7.6, respectively.

7.1. Comparison of the scenarios

The optimal values of the variables for all the five scenarios and those of the objective functions of the supply chain members and the total profit of the supply chain are presented in Tables (2) and (3), respectively. On that basis, the total profit of the supply chain is greater in the centralized scenario than in the others, and GHG emission is the least there. The alliance between the manufacturer and the first supplier in the third scenario provides the greatest total supply chain profit among the decentralized scenarios. The coalition members tend to reduce GHG emission and increase demand in the fifth scenario by having the second supplier share the costs, but the increase in revenue due to increased demand is less than the increase in the cost of reducing GHG emissions; therefore, total supply chain profit is less in this scenario than in the third. This feature

is also evident in comparing total supply chain profit in the second and fourth scenarios. It would not be economical in the fourth and fifth scenarios to have the second supplier share the cost of reducing GHG emissions. The GHG emissions in the fifth scenario are the lowest among those in the decentralized scenarios, and those in the fourth scenario are lower than those in the second. Hence, it is environmentally appropriate for the second supplier to share the cost of reducing GHG emissions. The difference in total supply chain profit between the third and fifth scenarios is less than the difference between them in GHG emissions, so the fifth scenario is the most suitable among the decentralized structures to balance the economic and environmental goals of the sustainable supply chain. The supply chain members must decide how to cooperate with each other according to the priority of economic and environmental goals in general. r (cost of reduction of GHG emission) is another important factor in the members' decision-making in cooperation with each other, and they are more willing to cooperate by reducing the parameter. It can be concluded from Table (3) through comparison of the second and third scenarios and of the fourth and fifth scenarios that the profit of the second supplier in the alliance between the manufacturer and first supplier is greater than that in the competition between them. In all five scenarios, the percentage of additives used is the same and equal to zero. According to Table (2), product price is higher in the second and fourth scenarios than in the others because of the competition between the supply chain members, so the products' demand is less in these scenarios than in the others. The price of raw materials required for the first product is higher than that for the second product in all five scenarios because the cost of raw materials and supply capacity for the first product are higher than those for the second product. The first product price is higher than that of the second because the price of raw materials required for the first product is higher.

Table (2) Optimal values of the decision variables

Scenario	l	Δ	x	p_1	p_2	d_1	d_2	w_1	w_2
1	0.18	0	958.98	53.59	43.71	200000	158753		
2	0.18	0	217.63	74.60	62.40	90428	72248	13.07	10.45
3	0.18	0	762.51	57.87	55.35	200000	85256		12.28
4	0.18	0	267.48	74.99	62.77	90080	72247	13.02	10.42
5	0.18	0	941.28	58.89	56.24	200000	86540		12.46

Table (3) Optimal values of the objective functions

Scenario	Z_{S_1}	Z_{S_2}	Z_M	$Z_M + Z_{S_1}$	$Z_M + Z_{S_1} + Z_{S_2}$
1					16117740
2	1168196.12	749429	9046404.96		10964020
3		1038369.2		14821222.98	15222580
4	1159200	727052.089	9076883.91		10963140
5		839529.739		14374099.49	15213630

7.2. Effect of the second supplier's share of the cost of reduction of GHG emission

This section investigates the effects of ρ on the supply chain members' variables and objective functions in the fourth and fifth scenarios. As shown in Table (4), the manufacturer's incentive to reduce GHG emissions increases as the second supplier's share of GHG reduction costs increases in the fourth scenario. The reduction of GHG emissions increases the manufacturer's non-production costs, and the manufacturer seeks to compensate for the loss by increasing the prices of its products, which leads to a slight decrease in the demand for them. The suppliers reduce their raw material prices by reducing product demand, and the suppliers' profits decrease as raw material prices and product demand are reduced according to Table (5). The decrease in the second supplier's profit is much greater than that for the first supplier because there is an increase in cost as well as a decrease in revenue. Besides, the total profit of the supply chain decreases with an increase in the second supplier's share of the cost of reducing GHG emissions. The above share is not economical for the supply chain in the fourth scenario but leads to a drastic decrease in GHG emission and is environmentally friendly. According to Table (6), the demand for the second product decreases in the fifth scenario with an increase in the second supplier's share of the cost of reducing GHG emission, as in the fourth scenario, but the demand for the first product remains constant. Table (7) shows that the coalition members increase their profits by increasing the prices of the products, and the profit of the second supplier decreases as the demand for the second product decreases. A sharp decline in the profit of the second supplier causes a decrease in the total profit of the supply chain, with an increase in the parameter. The reduction of GHG emissions in the fifth scenario is close to that in the centralized scenario, and the second supplier's profit decline is not severe where it has a 0.2 share of the coalition members' costs of reducing GHG emissions, which allows it to approach the ideal environmental goal of the sustainable supply chain, with an insignificant rate of decline in profit.

Table (4) Optimal values of the variables in the fourth scenario

ρ	x	p_1	p_2	d_1	d_2	w_1	w_2
0.1	239.95	74.77	62.57	90274.93	73342.60	13.046	10.435
0.2	267.48	74.99	62.77	90079.99	72246.55	13.019	10.421
0.3	302.22	75.26	63.03	89838.34	72127.877	12.984	10.404
0.4	347.48	75.606	63.36	89531.42	71975.54	12.94	10.382

Table (5) Optimal values of the supply chain members' objective functions in the fourth scenario

ρ	Z_{S_1}	Z_{S_2}	Z_M	$Z_M + Z_{S_1} + Z_{S_2}$
0.1	1164223.419	740150.874	9060027.416	10964400
0.2	1159200	727052.089	9076883.911	10963140
0.3	1152989.679	707582.635	9098291.28	10958860
0.4	1145125.046	677282.252	9126463.43	10948870

Table (6) Optimal values of the variables in the fifth scenario

ρ	x	p_1	p_2	d_1	d_2	w_1
0.1	850.08	58.35	55.73	200000	86213.32	12.42
0.2	941.28	58.89	56.24	200000	86540	12.46
0.3	1020.75	59.47	56.92	200000	85547.82	12.31
0.4	1119.43	60.18	57.75	200000	82255.05	12.14

Table (7) Optimal values of the supply chain members' objective functions in the fifth scenario

ρ	Z_{S_2}	$Z_M + Z_{S_1}$	$Z_M + Z_{S_1} + Z_{S_2}$
0.1	967877.384	14268476.93	15236530
0.2	839529.739	14374099.58	15213630
0.3	636935.772	14504220.88	15141160
0.4	362501.206	14677428.57	15029930

7.3. Effect of the manufacturer's budget

To investigate the effect of the budget parameter, it is assumed to vary from 1000000 to 3000000. The cost of reducing GHG emissions is higher than the other production costs, so the manufacturer and coalition members seek to reduce GHG emissions by increasing the budget to increase demand and profit. The pricing strategy of the supply chain members varies as the budgets for different products and scenarios increase. According to Figures (2a) to (2d), the manufacturer and coalition members seek to increase demand by reducing the price of the second product in all the scenarios and of the first product in the second and fourth scenarios. In the first, third, and fifth scenarios, the manufacturer cannot increase the demand for the first product due to the limited supply capacity for the raw materials of the first product and seeks to maximize profit by increasing price. According to Figure (2f), the total profit of the supply chain also increases in all the scenarios with an increase in the budget. The suppliers can increase the profits of the supply chain members and the total supply of the supply chain by increasing supply capacity where the supply chain members form the coalitions. The reduction of GHG emissions as the budget increases is greater in the third and fifth scenarios than in the second and fourth because price competition is less severe in the former scenarios. The rate of increase in total supply chain profit is higher in the second and fourth scenarios than in the others because customer demand is less in these scenarios due to price competition, and supply capacity limitations do not prevent the increase in the chain members' profits. It is economical to increase the budget in the scenarios where the supply chain members compete, and it is environment-friendly where they form alliances.

(a)

(b)

(c)

(d)

(e)

(f)

Figure (2) Effects of B on a) demand for the first product, b) demand for the second product, c) price of the first product, d) price of the second product, e) reduction of GHG emission, and f) supply chain profit.

7.4. Effect of the manufacture's capacity

The value of the parameter is assumed to lie between 120000 and 360000, and we can analyze its effect by considering the values of the other parameters as constant. The supply chain members seek to reduce the price to increase demand by raising production capacity according to Figures (3a) to (3d). The rate of price reduction is less in the second and fourth scenarios than in the others because there is severer competition for price in these scenarios. The competitive supply chain members cannot drastically reduce the product prices, so they decrease the cost of reducing GHG emissions by increasing them as shown in Figure (3e). GHG emissions decrease as production capacity increases in the first, third, and fifth scenarios, and they increase in the second and fourth scenarios. It is environment-friendly for the supply chain members who have formed coalitions to increase production capacity. According to Figure (3-f), the total profit of the supply chain increases in all the scenarios as supply capacity increases. The increase in the total profit of the supply chain is far greater in the first, third, and fifth scenarios than in the other two, so the increase in capacity is more economical in the scenarios where the supply chain members form alliances.

7.5. Effect of the cost of reducing GHG emission

We study the effects of the cost of reducing GHG emissions by having the value of the parameter range from 0.8 to 1.3. According to Figure (4e), GHG emission increases in all the scenarios with the increasing cost of reducing GHG emissions. The increase in GHG emission is greater in the first, third, and fifth scenarios than in the other two, so the increase in the cost of reducing GHG has a worse effect in terms of environmental goals for the supply chain members that form the coalition. Figures (4a) to (4d) show that the supply chain members cannot invest in reducing GHG emissions for all the scenarios due to increased cost. They determine a lower price to prevent a sharp decline in customer demand. Supply chain profit decreases in all the scenarios with the increase in the cost of reducing GHG emissions, according to Figure (4f). The total profit of the supply chain is higher in the fifth scenario than in the third, where r is less than one, and it is higher in the fourth scenario than in the second. The second supplier's share of the cost of reducing GHG is economical, where the cost is less than one, so the supplier's decision to share the cost with the manufacturer depends on the amount.

(a)

(b)

(c)

(d)

(e)

(f)

Figure (3) Effects of τ on a) price of the first product, b) price of the second product, c) demand for the first product, d) demand for the second product, e) reduction of GHG emissions, and f) supply chain profit.

(a)

(b)

(c)

(d)

(e)

(f)

Figure (4) Effects of r on a) price of the first product, b) price of the second product, c) demand for the first product, d) demand for the second product, e) reduction of GHG emissions, and f) supply chain profit.

7.6. Effect of government penalty on the endangerment of consumer health

According to Table (8), more fines are required for the coalition members' failure to use melamine in the third and fifth scenarios than in the second and fourth, so consumers are more likely to be endangered in the former scenarios. There is severer competition over price between the supply chain members in the second and fourth scenarios, and the manufacturer costs increase with an increase in the penalty parameter, so the manufacturer does not use melamine to prevent a decrease in demand. In these scenarios, the manufacturer prefers not to use melamine rather than to reduce price and increase GHG emissions to maintain the demand for the first product and increase that of the second product according to Figures (5- a) to (5-e). The percentages of melamine used in the third and fifth scenarios for different values of parameter g are higher than those for the second and fourth scenarios. Figures (5-a) to (5-e) show that the coalition members prefer to use melamine and reduce product price and GHG emissions to maintain the demand for the first product and increase that of the second product. The optimal values of the variables remain constant with an increase in the parameter in the second and fourth scenarios, so the total profit of the supply chain is constant in these scenarios as shown in Figure (5-f). In the centralized scenario, the decision-maker reduces the optimal value of melamine by increasing parameter g , seeking to prevent a decline in demand by reducing price and GHG emissions according to Figures (5-a) to (5-e), but these changes do not reduce the total profit of the supply chain as shown in Figure (5-f). An interesting result is obtained for the third and fifth scenarios, where total supply chain profit increases with an increase in the parameter. The demand for the second product increases with lower prices and less GHG emission and melamine use. The increase in demand leads to an increase in the total profit of the supply chain according to Figure (5-f). Total supply chain profit is higher in the fifth scenario than in the third, where g is less than 230.

Table (8) Optimal percentage of additives for different values of g

g	First Scenario	Second Scenario	Third Scenario	Fourth Scenario	Fifth Scenario
210	0.0001	1.72×10^{-8}	7.98×10^{-5}	0	4.82×10^{-5}
220	0.0001	0	5.78×10^{-5}	0	2.49×10^{-5}
230	9.8×10^{-5}	0	3.75×10^{-5}	0	2.65×10^{-6}
240	0	0	0	0	0

(a)

(b)

(c)

(d)

(e)

(f)

Figure (5) Effects of g on a) price of the first product, b) price of the second product, c) demand for the first product, d) demand for the second product, e) reduction of GHG emissions, and f) supply chain profit.

8. Conclusion

The food industry is one where consumer demand is constantly increasing, so companies must meet customers' new needs to maintain their competitive market positions. Today, quality and sustainability are among the main criteria for customers to buy food products. In this paper, it is assumed that the manufacturer reduces GHG emissions from the production process to increase customer demand. The reduction of greenhouse gas emissions increases manufacturer costs. Manufacturers use additives to reduce costs and increase demand, which may be detrimental to consumer health. The government imposes fines on the manufacturer for the use of additives to protect consumer health. All three dimensions of the sustainable supply chain are investigated for the problem addressed in this paper. Centralized and decentralized structures for the supply chain are studied, including one manufacturer and two suppliers. The goal of the centralized supply chain in the first model is to maximize total supply chain profit. Decentralized structures are considered for the supply chain in other scenarios. In the second scenario, the supply chain members compete to maximize profit. The manufacturer and the first supplier form an alliance in the third scenario. The second supplier shares the cost of reducing GHG emissions in the fourth scenario. The first supplier allies with the manufacturer, and the second one shares the cost of reducing GHG emissions in the fifth scenario. The first model is solved as a single-level model, and bi-level programming is used to model the other scenarios.

The above five scenarios have been solved for a numerical example, and the results demonstrate that the total profit of the supply chain in the third scenario is the greatest among those in the decentralized scenarios, and GHG emissions are least in the fifth scenario among the decentralized scenarios. It is economical to increase the budget in the scenarios where the supply chain members compete. Moreover, it is environment-friendly to increase production capacity and the budget for the supply chain members that have formed coalitions. The difference between the total profits of the supply chain in the third and fifth scenarios is less than that between the GHG emissions in the two scenarios, so the fifth scenario is appropriate for the achievement of a balance between the economic and environmental goals of the sustainable supply chain, as compared to the other decentralized structures. The total profits of the supply chain in the fourth and fifth scenarios decrease as the second supplier's share of the cost of reducing GHG emission increases. The amount of reduction of GHG emissions in the fifth scenario is close to the value of the variable in the centralized scenario, and the second supplier's profit decline is not severe, where the second supplier has a 0.2 share of the cost of reducing GHG emissions. The total profit of the supply chain in the fifth scenario is higher than that in the third scenario where r is less than one, and the total profit of the supply chain in the fourth scenario is higher than that in the second scenario under the same conditions. Consumer health is at higher risk in the first, third, and fifth scenarios than in the others. Uncertainty and risk management have gained plenty of significance in the food supply chain, so these issues should be considered in future research on the food supply chain.

883 Furthermore, different criteria can be considered for the environmental and social dimensions of
884 the food supply chain.

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Appendix (1)

A non-empty, convex, closed solution space for the players is the first condition to obtain at least one solution for the game between them (Mahmoodi, 2019; Matsumoto and Szidarovszky, 2016). According to Relations (13) and (14), the problem constraints are linear for the suppliers, and the solution space is non-empty and convex. The value of the product demand function is greater than or equal to zero, so the product of the positive parameter by demand is also positive, and Relations (24) and (25) are always valid for the problem. According to Relations (24) and (26), the price of the first product is obtained based on the percentage of additives and reduction of GHG emission, which are constrained by Relations (6) and (8), so the price of the first product is limited to the range obtained in Relation (27). The same procedure is gone through for the price of the second product, and Relation (28) is obtained according to Relation (25), limiting the price of the second product to the range obtained in Relation (29). According to Relation (3), the price of each product is greater than or equal to the price of the raw materials of each supplier $p_i \geq w_i$. It has been proven that the product price variables are limited, so those involving the prices of raw materials are also limited, and their solution space is therefore closed. It has been proven that the solution space for the supplier variables is non-empty, convex, and closed, so the first condition has been proven to be valid.

$$0 \leq \alpha d_1 + \delta d_2 \quad (24)$$

$$0 \leq \delta d_1 + \alpha d_2 \quad (25)$$

$$p_1 \leq \frac{(\alpha + \delta)(\beta x + \gamma \Delta) + \bar{d}(\alpha \mu_1 + \delta \mu_2)}{\alpha^2 - \delta^2} \quad (26)$$

$$p_1 \leq \frac{(\alpha + \delta)(\beta e + \gamma u) + \bar{d}(\alpha \mu_1 + \delta \mu_2)}{\alpha^2 - \delta^2} \quad (27)$$

$$p_2 \leq \frac{(\alpha + \delta)(\beta x + \gamma \Delta) + \bar{d}(\alpha \mu_2 + \delta \mu_1)}{\alpha^2 - \delta^2} \quad (28)$$

$$p_2 \leq \frac{(\alpha + \delta)(\beta e + \gamma u) + \bar{d}(\alpha \mu_2 + \delta \mu_1)}{\alpha^2 - \delta^2} \quad (29)$$

As can be seen, each supplier's objective function is continuous with respect to the corresponding variable (raw material price). The second derivative of the objective function of each supplier is negative with respect to the wholesale price of its raw materials ($\frac{\partial^2 Z_{S_i}}{\partial w_i^2} = -2\alpha$), so the objective function is concave. The supplier objective functions are continuous and concave, so the second and third conditions for the suppliers are valid to obtain at least one solution in the game between them.

Appendix (2)

It has been proven in lemma (1) that the game between the suppliers has at least one solution. It is sufficient to demonstrate that the game is strictly concave diagonal to prove the uniqueness of the solution (Mahmoodi, 2019; Matsumoto and Szidarovszky, 2016). First, $A(w_i, r)$ is obtained for the suppliers according to Relation (30).

$$A(w_i, r) = \begin{pmatrix} A_1(w_i, r) \\ A_2(w_i, r) \end{pmatrix} = \begin{pmatrix} r_1 \nabla_1 Z_{S_1} \\ r_2 \nabla_2 Z_{S_2} \end{pmatrix} = \begin{pmatrix} r_1 (\mu_1 \bar{d} + \beta x + \gamma \Delta + \alpha(c_1 - v_1 - 2w_1) + \delta(v_2 + w_2)) \\ r_2 (\mu_2 \bar{d} + \beta x + \gamma \Delta + \alpha(c_2 - v_2 - 2w_2) + \delta(v_1 + w_1)) \end{pmatrix} \quad (30)$$

It must be demonstrated that $J(w_i, r) + J^T(w_i, r)$ is negative definite to prove that the game between the suppliers is strictly concave diagonal. $J(w_i, r)$ is Jacobin's matrix with respect to the w_i variable for $A(w_i, r)$, as presented in Relation (31). We know that $-4\alpha r_1$ is always smaller than zero, so the first condition for the matrix holds given Relation (32). The matrix determinant is calculated in Relation (33), and we know that $\alpha > \delta$ holds for the model. It can be concluded from Relation (34) that the determinant of the matrix is always positive, and the matrix is negative definite if parameters r_1 and r_2 are set to 1. According to these relations, the matrix $J(w_i, r) + J^T(w_i, r)$ is negative definite, and the game between the two suppliers is strictly concave diagonal, so it has a unique solution.

$$J(w_i, r) = \begin{pmatrix} \frac{\partial A_1(w_i, r)}{\partial w_1} & \frac{\partial A_1(w_i, r)}{\partial w_2} \\ \frac{\partial A_2(w_i, r)}{\partial w_1} & \frac{\partial A_2(w_i, r)}{\partial w_2} \end{pmatrix} = \begin{pmatrix} -2\alpha r_1 & \delta r_1 \\ \delta r_2 & -2\alpha r_2 \end{pmatrix} \quad (31)$$

$$J(w_i, r) + J^T(w_i, r) = \begin{pmatrix} -2\alpha r_1 & \delta r_1 \\ \delta r_2 & -2\alpha r_2 \end{pmatrix} + \begin{pmatrix} -2\alpha r_1 & \delta r_2 \\ \delta r_1 & -2\alpha r_2 \end{pmatrix} = \begin{pmatrix} -4\alpha r_1 & \delta(r_1 + r_2) \\ \delta(r_1 + r_2) & -4\alpha r_2 \end{pmatrix} \quad (32)$$

$$\det(J(w_i, r) + J^T(w_i, r)) = 16r_1 r_2 \alpha^2 - \delta^2 (r_1 + r_2)^2 \quad (33)$$

$$\det(J(w_{it}, r) + J^T(w_{it}, r)) = 16\alpha^2 - 4\delta^2 \quad (34)$$

Appendix (3)

There is no difference between the solution spaces for the suppliers in the second and fourth scenarios, so the solution space is non-empty, convex, and closed for the suppliers in both scenarios. It can be seen from Relations (12) and (18) that the suppliers' objective functions are continuous. The second derivative of the objective function of each supplier is negative with

respect to the wholesale price of its raw materials ($\frac{\partial^2 Z_{S_i}}{\partial w_{it}^2} = -2\alpha$), so the objective function is concave, and the game between the suppliers has at least one solution.

Appendix (4)

The approach adopted for proof in lemma (1) is repeated in this section. $A(w_i, r)$ is obtained for the fourth scenario in Relation (35) with the assumption $r_1, r_2 \geq 0$. $A(w_i, r)$ is the same for the second and fourth scenarios, so the matrix $J(w_i, r) + J^T(w_i, r)$ is negative definite. It can be concluded that the game between the suppliers in the fourth model is strictly concave diagonal and has a unique solution.

$$\begin{aligned} A(w_i, r) &= \begin{pmatrix} A_1(w_i, r) \\ A_2(w_i, r) \end{pmatrix} = \begin{pmatrix} r_1 \nabla_1 Z_{S_1} \\ r_2 \nabla_2 Z_{S_2} \end{pmatrix} \\ &= \begin{pmatrix} r_1(\mu_1 \bar{d} + \beta x + \gamma \Delta + \alpha(c_1 - v_1 - 2w_1) + \delta(v_2 + w_2)) \\ r_2(\mu_2 \bar{d} + \beta x + \gamma \Delta + \alpha(c_2 - v_2 - 2w_2) + \delta(v_1 + w_1)) \end{pmatrix} \end{aligned} \quad (35)$$

Appendix (5)

This proof assumes that the supplier has sufficient capacity, and Relation (13) is not considered for solving the problem. Price equilibrium is obtained for the suppliers through the equation of the first derivative of the supplier profit function concerning the raw material price variable to zero in Relation (36).

$$w_i^* = \frac{(2\alpha^2(c_i - v_i) + \delta^2 v_i + \delta(\mu_{3-i} \bar{d} + \Delta \gamma + \beta x) + \alpha(2\mu_i \bar{d} + 2\Delta \gamma + \delta(c_{3-i} + v_{3-i}) + 2\beta x))}{4\alpha^2 - \delta^2} \quad (36)$$

$$\frac{\partial w_i}{\partial \alpha} = -\frac{(4\alpha^2 + \delta^2)U_i^1 + 4\alpha\delta(\delta(c_i + v_i) + 2(\Delta \gamma + \beta x + \mu_{3-i} \bar{d}))}{(4\alpha^2 - \delta^2)^2} \quad (37)$$

$$\frac{\partial w_i}{\partial \delta} = \frac{4\alpha^3(c_{3-i} + v_{3-i}) + (4\alpha^2 + \delta^2)(\Delta \gamma + \beta x + \mu_{3-i} \bar{d}) + 4\alpha^2\delta(c_i + v_i) + U_i^2}{(4\alpha^2 - \delta^2)^2} \quad (38)$$

The numerators and denominators of both fractions are always positive according to Relations (37) and (38), so $\frac{\partial w_i}{\partial \alpha} \leq 0$, $\frac{\partial w_i}{\partial \delta} \geq 0$.

The raw material price equilibrium is placed in the supplier demand and profit functions, and the first derivative of the profit function is obtained with respect to two parameters.

$$\frac{\partial Z_{S_i}}{\partial \alpha} = \frac{(2\alpha^2(c_i + v_i) - \delta(\mu_{3-i} \bar{d} + \Delta \gamma + \delta(c_i + v_i) + \beta x) - \alpha(\delta(c_{3-i} + v_{3-i}) + 2(\mu_i \bar{d} + 2\Delta \gamma + 2\beta x)))U_i^3}{(4\alpha^2 - \delta^2)^3} \quad (39)$$

$$\frac{\partial Z_{S_i}}{\partial \delta} = -\frac{2\alpha(2\alpha^2(c_i + v_i) - \delta(\mu_{3-i} \bar{d} + \Delta \gamma + \delta(c_i + v_i) + \beta x) - \alpha(\delta(c_{3-i} + v_{3-i}) + 2(\mu_i \bar{d} + 2\Delta \gamma + 2\beta x)))U_i^4}{(4\alpha^2 - \delta^2)^3} \quad (40)$$

1031 We know that $\alpha > \delta$, and the numerators of both fractions are negative according to Relations (39)
 1032 and (40); therefore, $\frac{\partial Z_{s_i}}{\partial \alpha} \leq 0, \frac{\partial Z_{s_i}}{\partial \delta} \geq 0$.

$$\begin{aligned} U_i^1 &= \delta(c_{3-i} + v_{3-i}) + 2(\Delta \gamma + \beta x + \mu_i \bar{d}), U_i^2 \\ &= \alpha \delta \left(\delta(c_{3-i} + v_{3-i}) + 4(\Delta \gamma + \beta x + \mu_i \bar{d}) \right) \end{aligned} \quad (41)$$

$$\begin{aligned} U_i^3 &= (8\alpha^4(c_i + v_i) + \delta^3(\Delta \gamma + \mu_{3-i} \bar{d} + \delta(c_i + v_i) + \beta x) + 4\alpha^3(\delta(c_{3-i} + v_{3-i}) \\ &\quad + 2(\Delta \gamma + \mu_i \bar{d} + \beta x)) \\ &\quad + 3\alpha\delta^2(\delta(c_{3-i} + v_{3-i}) + 2(\Delta \gamma + \mu_i \bar{d} + \beta x)) + 2\alpha^2\delta(\delta(c_i + v_i) + 6(\Delta \gamma + \mu_{3-i} \bar{d} \\ &\quad + \beta x))) \end{aligned} \quad (42)$$

$$\begin{aligned} U_i^4 &= 4\alpha^3(c_{3-i} + v_{3-i}) + \delta^2(\Delta \gamma + \mu_{3-i} \bar{d} + \beta x) + 4\alpha^2(\Delta \gamma + \mu_{3-i} \bar{d} + \beta x + \delta(c_i \\ &\quad + v_i)) + \alpha\delta(\delta(c_{3-i} + v_{3-i}) + 4(\Delta \gamma + \mu_i \bar{d} + \beta x)) \end{aligned} \quad (43)$$

1033 Appendix (6)

1034 The difference between the wholesale prices of raw materials is obtained in Relation (44).

$$w_2 - w_1 = \frac{\bar{d}(-\mu_1 + \mu_2) + \delta(v_1 - v_2) + \alpha(-c_1 + c_2 + v_1 - v_2)}{2\alpha + \delta} \quad (44)$$

1035 If $\frac{\bar{d}(\mu_2 - \mu_1) + \alpha(c_2 - c_1)}{\alpha + \delta} \geq v_2 - v_1$, then $w_2 \geq w_1$; otherwise, $w_2 < w_1$.

1036 The difference in the demand for the products is obtained in Relation (45).

$$d_2 - d_1 = \frac{\bar{d}(-\mu_1 + \mu_2) + \delta(v_1 - v_2) + (\alpha + \delta)(c_1 - c_2 + v_1 - v_2)}{2\alpha + \delta} \quad (45)$$

1037 If $\frac{\bar{d}(\mu_2 - \mu_1)}{\alpha + \delta} + c_1 - c_2 \geq v_2 - v_1$, then $d_2 \geq d_1$; otherwise, $d_2 < d_1$.

1038 Appendix (7)

1039 We obtain the first derivative of the profit function of the second supplier with respect to the price
 1040 of raw materials and set it to zero, assuming sufficient capacity for the second supplier, and the
 1041 equilibrium of the wholesale price of raw materials for the second product is obtained in Relation
 1042 (46).

$$w_2^* = \frac{\mu_2 \bar{d} + \alpha c_2 + \Delta \gamma + \delta p_1 - \alpha v_2 + \Delta \gamma}{2\alpha} \quad (46)$$

$$\frac{\partial w_2}{\partial \alpha} = - \frac{\Delta \gamma + \mu_2 \bar{d} + \delta p_1 + \Delta \gamma}{2\alpha^2} \quad (47)$$

$$\frac{\partial w_2}{\partial \delta} = \frac{p_1}{2\alpha} \quad (48)$$

1043 The numerators and denominators of both fractions in Relations (47) and (48) are always positive,
 1044 so $\frac{\partial w_2}{\partial \alpha} \leq 0, \frac{\partial w_2}{\partial \delta} \geq 0$.

1045 The equilibrium of the price of raw materials is placed in the demand and profit functions of the
 1046 second supplier, and the first derivative of the profit of the second supplier is obtained with respect
 1047 to two parameters.

$$\frac{\partial Z_{S_2}}{\partial \alpha} = - \frac{(\Delta \gamma + \beta x + \mu_2 \bar{d} + \delta p_1 - \alpha(c_2 + v_2))(\Delta \gamma + \beta x + \mu_2 \bar{d} + \delta p_1 + \alpha(c_2 + v_2))}{4\alpha^2} \quad (49)$$

$$\frac{\partial Z_{S_2}}{\partial \delta} = \frac{p_1(\Delta \gamma + \mu_2 \bar{d} + \delta p_1 - \alpha(c_2 + v_2) + \beta x)}{2\alpha} \quad (50)$$

1048 We know that $d_2 \geq 0$, so $\Delta \gamma + \beta x + \mu_2 \bar{d} + \delta p_1 - \alpha(c_2 + v_2) \geq 0$. The numerators and
 1049 denominators of both fractions in Relations (49) and (50) are always positive, so $\frac{\partial Z_{S_2}}{\partial \alpha} \leq 0, \frac{\partial Z_{S_2}}{\partial \delta} \geq$
 1050 0.

1051 Appendix (8)

1052 The difference between the prices of the products is obtained in Relation (51).

$$p_1 - p_2 = - \frac{\Delta \gamma + \mu_2 \bar{d} + \delta p_1 + \alpha(c_2 - 2p_1 + v_2) + \beta x}{2\alpha} \quad (51)$$

1053 If $p_1(2\alpha - \delta) - \alpha v_2 \geq \mu_2 \bar{d} + \beta x + \gamma \Delta + \alpha c_2$, then $p_1 \geq p_2$; otherwise, $p_1 < p_2$.

1054 The difference in the demand for the products is obtained in Relation (52).

$$d_2 - d_1 = - \frac{\alpha^2(c_2 - 2p_1 + v_2) + \delta(\Delta \gamma + \beta x + \mu_2 \bar{d} + \delta p_1) + \alpha(\Delta \gamma + \beta x + 2\mu_1 \bar{d} - \mu_2 \bar{d} + \delta(c_2 - p_1 + v_2))}{2\alpha} \quad (52)$$

1055 If $p_1(2\alpha - \delta)(\alpha + \delta) - \alpha(\alpha - \delta)v_2 \geq \epsilon$, then $d_2 \geq d_1$; otherwise, $d_2 < d_1$.

1056 where $\epsilon = \alpha^2 c_2 + (\alpha + \delta)(\beta x + \gamma \Delta) + \bar{d}(2\mu_1 \alpha + \mu_2(\alpha - \delta))$.

1057

1058

Appendix (9)

Let us consider the following optimization problem.

$$\text{Max } f(x) \quad (53)$$

$$\text{subject to } g_i(x) \geq 0 \quad i = 1, m \quad (54)$$

$$h_j(x) = 0 \quad j = 1, l \quad (55)$$

The Slater condition is valid for the problem if the objective functions and constraints are hyper-concave, and $\bar{x}$ is obtained such that $g_i(\bar{x}) > 0, h_j(\bar{x}) = 0$. The objective functions of the suppliers in the second to fifth scenarios are concave. All the constraints are linear, so they are both concave and convex. The percentage of additives and the reduction of GHG emissions are assumed to be zero in the above scenarios. The price of each product is calculated according to Relation (56), where ε is a very small value. The demand for each product is $(\alpha - \delta)\varepsilon$ according to the prices, percentage of additives, and reduction of GHG emission. The capacity of each supplier s_i is set to a value greater than $(\alpha - \delta)\varepsilon$, so Relation (13) is inactive for the suppliers. Therefore, the Slater quality condition is valid, and the optimal values of the variables can thus be obtained as KKT conditions are set for the suppliers.

$$p_i = \frac{(\alpha \mu_i + \delta \mu_{3-i}) \bar{d}}{(\alpha^2 - \delta^2)} - \varepsilon, \quad \forall i \quad (56)$$