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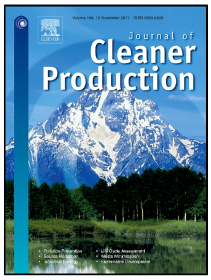

A game theoretic approach for green and non-green product pricing in chain-to-chain competitive sustainable and regular dual-channel supply chains

Mohammad-Bagher Jamali, Morteza Rasti-Barzoki

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Highlights

- Pricing in Chain-to-Chain Competition of Dual–Channel Supply Chains.
- The producer can sell products to customers through both the internet the retailer.
- Considering one green-product and one non-green product competitor manufacturers.
- A Stackelberg competition is established between the members of each supply chain.
- A Nash competition is established between two supply chains.

A game theoretic approach for green and non-green product pricing in chain-to-chain competitive sustainable and regular dual-channel supply chains

Mohammad-Bagher Jamali[a], Morteza Rasti-Barzoki[b*]

[a] *M.Sc. student, Department of Industrial and Systems Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran*

[b] *Ph.D., Department of Industrial and Systems Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran*

Abstract

Nowadays, sustainable supply chain has become an exciting concept during the academic societies. This paper considers environmental and economic aspect of sustainability. Due to environmental concerns, the entry of green products into today's markets is on the rise. How to compete for the production of green products with non-green products is essential in these markets. Therefore, this research focuses on the pricing and determination of the degree of greenness of a product in competition with a non-green product. This study, for the first time, investigates the pricing of two substitute products, a green product produced by one manufacturer and a non-green product produced by a second manufacturer, under two dual-channel supply chains including retail and internet channels. The decision variables for one manufacturer are the price and degrees of eco-friendliness of the green product; for the other, the decision variable is the price of the non-green product. This problem is solved under two different scenarios: centralized and decentralized. In the decentralized scenario, a Stackelberg competition is considered between the retailer level and the manufacturer level of the total supply chains in which the manufacturers are assumed to be the leader, and the retailers are the followers. In the centralized scenario, players in each of their related supply chain are integrated. The problem is solved and compared under two scenarios. Finally, both parametric and numerical analyses are presented and some managerial insights are provided and some of which are as follows: The centralized scenario cause to achieve high the green degree comparing with the decentralized scenario.

* Corresponding author; Tel.: +983133911480; Fax: +983133915526.

E-mail address: rasti@cc.iut.ac.ir (Morteza Rasti-Barzoki)

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1. Introduction

Sustainable development is one of the most important issues from both the theoretical and practical points of view. Concepts and issues of sustainability are implemented in supply chains for many manufacturing organizations (Frostenson and Prenkert, 2015). With more social awareness of these issues, awareness of environmental damage caused by economic activities has become important for governments and economic institutions in the context of sustainable development. These days, organizations are not able to ignore environmental issues (Yang et al., 2011). In recent years, environmental concerns, regulatory pressures and competitive and complex environmental regulations have led organizations toward green supply chains (Diabat et al., 2014). Therefore, investigation of green supply chains has attracted many researchers all over the world (Karakayali et al., 2007). Many factors are involved in the management of supply chains, including financial and non-financial effectiveness, green areas of activity, and outputs or performance (Lin and Tseng, 2016).

One of the most important factors in green activities is green production, which plays an important role in the development of green supply chain management, considering decision making processes (Li et al., 2016). To achieve sustainable supply chains, the production of green products must be expanded (Watkins et al., 2016). Green products are described those that have fewer negative effects on human health and the environment. This concept involves sustainable supply chains, environmental sustainability, and a green planet where standard technologies are used (Palevich, 2011). The novelty of green production is that it increases competitive advantages as well as improving the environment (Seuring, 2013). Therefore, many companies have concentrated on green product generation and considering that part of their practical programs (Ghosh and Shah, 2012). On the other hand, some of the most important decisions in recent competitive markets concern pricing, advertising and selling channels (Ji et al., 2017; Yi et al., 2016). In addition, rapid development of E-commerce and information technology in the past few decades have had a significant influence on the buying behavior of customers and has led to redesign and changes in the strategy of supply chain distribution of many producers (Hua et al., 2010). Nowadays, manufacturers sell their products using multi-channel strategies, such as retailers, selling on the internet or a combination of these two strategies. Many companies such as Apple, IBM and Dell use dual-distribution channels (Huang et al., 2013b). In direct channels, products are received directly from producers by consumers; in indirect channels, products are passed to retailers, who then sell them to customers. Direct channels allow producers to reduce their costs and increase their income at the same time and create new markets for their products (Chen et al., 2012).

Based upon the above explanation, an incentive is arisen to study the entry of green products into today's markets and examine how producers of green product compete with non-green product manufacturers. Usually, previous studies focused only on economic goals, and studies on green issues often investigated in closed-loop or reverse supply chain. In this paper, in addition to our economic goals, an environmental sustainability index, the greenness of product is surveyed. We answer the following questions in this article:

(1) How much is equilibrium green product price versus non-green products in direct and indirect channels?
(2) What are the effects of different parameters on the degree of greenness of the product?
(3) How can the supply chain be improved to a sustainable supply chain?
(4) What are the causes of demand and profit functions of green supply chain members?

To answer these questions, in this paper, the problem of pricing green and non-green products in two-competitor two-stage supply chains with dual distribution channels is investigated; a game theory approach is used for modeling and solving the problem. The novelty of this paper is its examination of competition between a green supply chain and a non-green supply chain in which both supply chains use one direct channel and one retail channel to sell their products to customers. To our knowledge, this problem has not previously been addressed.

The rest of this paper is organized as follows. In Section 2, a literature review is presented. Section 3 presents assumptions, the problem structure and the model definition. In Section 4 presents game instructions and a solution to the problem. Section 5 is allocated to parametric sensitivity analysis. In Section 6, a numerical example is presented for better understanding. Finally, conclusions and future research suggestions are presented in Section 7.

2. Literature review

Green supply chain management is a type of developed supply chain management that is concerned with being green, a stable environment, waste reduction, and optimum use of resources (Zhu et al., 2012). Green supply chain management is defined as materials management, production, and purchasing of green products, as well as their marketing and distribution (Hervani et al., 2005). Some practices such as pollution prevention, green supply-chain management and development of green products play an important role in determining the Company's financial performance (Miroshnychenko et al., 2017). Support management decision making helps corporations to identify a set of these strategies for green supply-chain management, have an impact on the environment and economic performance of companies in the supply chain (Carvalho et al., 2017). Many studies have taken a game theory approach to analyzing the issues arising in green supply chain management.

Competition between providers and producers that provide products with reusable components is considered in one green supply chain by Sheu (2011). Sheu and Chen (2012) checked out competition among providers and manufacturers, using game theory in a three-stage supply chain. Their results showed that in uncertainty conditions, green product generation could have a green non-negative profit for producers. Barari et al. (2012) presented an evolutionary game model that considers production of green commodities by a producer that are delivered to customers by a retailer. Coordination between the manufacturer and the retailer may have environmental benefits and commercial advantages. Ghosh and Shah (2012) considered a two-stage supply chain consisting of one retailer and customers in which products are delivered to customers from the manufacturer by retailers. They considered the intention to produce green products, and investigated influence of channel structures on the prices and profits for green goods; they also surveyed the effect of green costs and customer sensitivity on production of green commodities. They used a game theory approach for solving the problem. Cao and Zhang (2013) believed variety in the usefulness of green products creates market demand; they coordinated a green channel between providers and manufacturers with a pricing strategy. The green effect of products on market demand in a three-stage supply chain including a supplier, a manufacturer and a retailer was studied by Zhang and Liu (2013). The green degree of products was assumed to be constant, and a Stackelberg game was used for three levels of their model. Zhang et al. (2014) considered a manufacturer that receives required raw materials from a supplier; green and non-green products are produced. Both cooperative and non-cooperative approaches to solving the game between the supplier and the manufacturer were taken into account. Huang et al. (2016) considered a green supply chain that included several suppliers, one manufacturer and several retailers. A model based on game theory was developed to investigate the simultaneous effects of production line design, supplier selection, and choice of transport strategies on profit and control of greenhouse gas emissions.

Zhang et al. (2016) considered a green supply chain consisting of a provider and a retailer. The producer determines the level of energy efficiency and the wholesale price, and the retailer determines the selling price. Aydin et al. (2016) surveyed coordination between a supplier and other players for production line design in a closed-loop supply chain. The production line includes new and remanufactured products. A multi-objective optimization model was formulated based on a Stackelberg game. Li et al. (2016) surveyed a supply chain considering dual-channel distribution in which a manufacturer produces a green commodity and delivers it to final customers through direct and retailer channels. In addition, they considered green cost in their model and solved the problem in both centralized and decentralized states by using a game theory approach and compared the results. Basiri and Heydari (2017) investigated a supply chain that sells a non-green product and also intends to sell a new green product. In the supply chain, the decision variables for the retailer are the sale price and effort level for selling green product and the decision variables for the manufacturer is green product quality. Their study modeled and solved the problem it using a game-theoretic approach.Yang and Xiao (2017) evaluated the pricing and the green level of the product in a green supply chain under government intervention. In this problem, manufacturing cost and product demand are under fuzzy uncertainty. This problem was solved by a game-theoretic approach. Madani and Rasti-Barzoki (2017) studied pricing strategies, the degree of green product and the role of government tariffs in two green and non-green supply chains, each containing a manufacturer and a retailer. To solve the problem a Stackelberg game was considered in which the government as a leader and supply-chains as the followers. (Zhu and He, 2017) investigated pricing competition and product green degree competition in order to green product design in different structures of the supply chain. The problem is solved by a game-theoretic approach.

Some of these papers discuss the pricing and greenness of green products. However, in neither of them, pricing and determining the amount of greenness has not been investigated when the presence of a competitor with non-green that both products sell their products through dual distribution channels, including Internet channels and retailers. In this study, two supply chains, one green and one non-green producers are considered; in both supply chains, the producer can sell products to customers through both a direct channel and an indirect channel. In fact, the current paper investigates the pricing policy for the green and non-green products as well as the green degree for the green product under competition of the two dual channel supply chains for the first time. In the first supply chain (SC_1), the manufacturer generates green commodities and sells them to the first retailer at a wholesale price, or sells them directly to the end customers at a different price. In addition, the retailer sells them to the customers at a price different from both the wholesale and direct prices. In the second supply chain (SC_2), the process of pricing and selling to the customers is carried out similarly to the first supply chain. The aim of this paper is to determine the prices in the different channels. In addition, the green degree of the commodity produced by the first manufacturer is determined. Therefore, the main contributions of this study can be presented as follows.

- Pricing in chain-to-chain competition of dual–channel supply chains is taken into consideration.
- It is assumed that the producer can sell products to customers through both the internet and the retailer.
- One green-product and one non-green product competitor manufacturers are considered.

- A game-theoretic approach is considered, and the equilibrium variables are calculated under two different scenarios.

3. Problem statement and formulation

This section first defines the notations used in the study. Then, the problem and structure that is studied is explained in detail and mathematical modeling of the problem is performed.

3.1 Notations

The following notations are used.

Indices

i Index of manufacturers ($i = 1,2$)
j Index of channels: retailer ($j = r$) or direct ($j = d$)

Parameters

α_{ij} Market base for manufacture i in channel j
β Self-price elasticity of demand
λ_i Sensitivity coefficient amounts of green degree per unit of manufacture i's product on demand
μ Cost-coefficient of green degree
γ Cross-price elasticity of demand
w_i Wholesale price manufacture i's product
c_i The cost of production for manufacture i

Decision variables

p_{ij} The final price of manufacture i's product in channel j
θ The green degree of the first manufacture's product

Dependent Variables

D_{ij} Demand for manufacture i's product through channel j
π_{Mi} Profit function of manufacture i
π_{ri} Profit function of retailer i

3.2 Problem definition

Two-competitor supply chains with dual-distribution channels are taken into account. In both supply chains, there is one manufacturer that produces one commodity and sells it to the customers through a retailer or a direct channel. So, each supply chain consists of one manufacturer and one retailer. The first manufacturer's commodity is green that its green degree is determined by the manufacturer. Both supply chains tend to maximize their profit. This problem is solved under two different scenarios: centralized (C) and decentralized (DC). In the decentralized scenario, it is assumed that there is Nash competition between the retailers in each supply chain; consequently, a Nash equilibrium can be calculated. In Nash competition, players have the same power and decisions are made simultaneously. In addition, there is Stackelberg competition between the retailer level and manufacturer level of the total system. In other words, manufacturer-level decisions are initially made, and then retailer-level decisions are made based on the manufacturer's decisions. Thus, manufacturers are considered leaders and retailers are followers. Eventually, there is Nash competition between two manufacturers to determine their wholesale prices. The power structure for solving the problem is shown in Fig. 1. In the centralized scenario, Manufacturer and retailer in each supply chain are integrated. Therefore, in this scenario, competition is between SC_1 and SC_2. A Nash competition between two supply chains is considered.

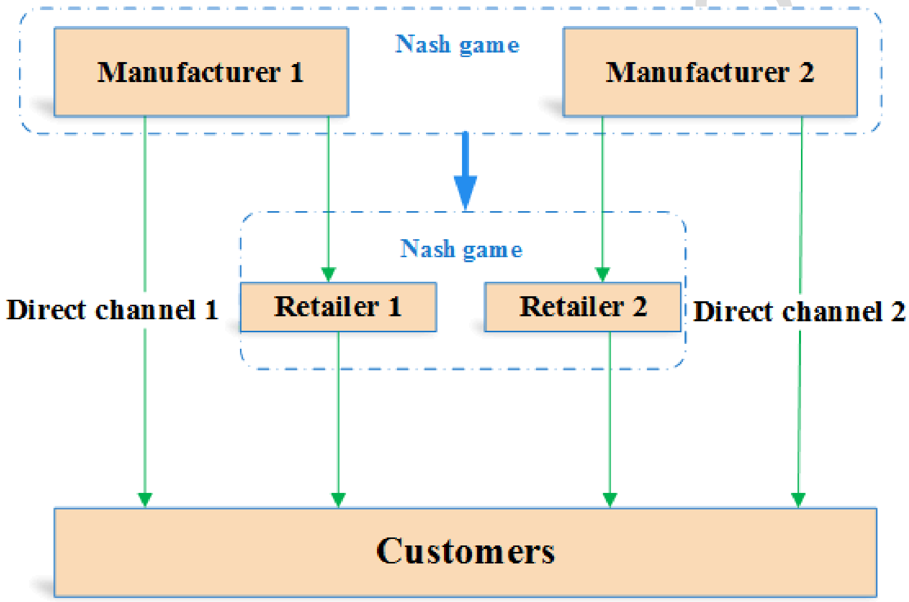

Fig. 1. Problem structure and schematic Nash and Stackelberg games between players

3.3 Materials and methods

The problem investigated during the study contains several agents (players). In addition, the decision of each agent effected on the decisions of other agents. In order to the analysis of interactive situations and identification the behavior of players the problem is formulated and solved through a game-theoretic approach. Game theory attempts to give a mathematical and logical form in order to achieve the best outcome by playing the right action among all actions that players might choose. There are different strategies in a game-theoretic environment and several ways of classifying games exist in the literature review. One of the most well-known methods classifies the games into two groups: cooperative and non-cooperative. Based on this classifying methods, in this paper, two different scenarios are considered: centralized and decentralized.

3.4 Assumptions

The model is constructed based on the following assumption.

Assumption 1. Linear cost function

Cost functions are assumed to be linear for the manufacturers and the retailers so that the results are explicit, and the parameters can easily be estimated (Huang et al., 2013a). This assumption has been made in most studies, such as Choi (1996); Huang and Swaminathan (2009); Jafari et al. (2016); Raju and Roy (2000).

Assumption 2. ($p_{ir} > w_i > c_i$)

Retailer prices must be more than wholesale prices because of the requirement for positive profit for retailers. In addition, in order to have positive profit for manufacturers, wholesale prices have to be more than the manufacturing cost of the products. This assumption has been considered in many studies (for instance see (Chaab and Rasti-Barzoki, 2016; Jafari et al., 2017; Li et al., 2016; Xiao and Shi, 2016)).

Assumption 3. ($\beta > \lambda_i > 0$)

It is assumed that the self-price coefficient is more important than the green degree, which is also a common assumption in the literature Cai et al. (2009); Chen et al. (2012); Li et al. (2016).

Assumption 4. ($\beta > \gamma > 0$)

The importance of self-price in one channel against cross-price of the other channel is another assumption. Due to increases in the unit price, the number of customers who give up a channel is greater than the number of another channel's customers who switch to this channel due to increases in the unit price of the other channel. In articles such as Chen et al. (2013); Dan et al. (2012); Lu et al. (2011), this assumption is mentioned.

Assumption 5. ($\lambda_1 > \lambda_2$)

This paper uses indices λ_1 and λ_2 for the effect of green degree of the first commodity on demand in the first and second supply chains, respectively. Green degree is an important factor in increased demand for products for the first manufacture and retailer. There is also a slight decrease in the cost function of the second manufacture and retailer, because their products aren't green and aren't attractive enough to customers. This assumption shows that customers would rather buy green products. If green products aren't available, then they switch to second supply chain. The ratio of people interest in buying non-green product is λ_2. The different between indices λ_1 and λ_2 determines the number of people who give up buying the non-green product. This assumption is used in some articles including Li et al. (2016).

Assumption 6. $C(\theta) = \mu\frac{\theta^2}{2}$

The first manufacturer must spend more to produce the green product. In this paper, the cost function of the green product is considered as a second order cost function ($C(\theta) = \mu\frac{\theta^2}{2}$). This type of cost function is considered in different studies (i.e. (Gao et al., 2016; Li et al., 2016; Swami and Shah, 2013)).

3.5 The demand functions

The demand functions for each channel are shown in Eqs. (1)-(4).

$$D_{1d} = \alpha_{1d} - \beta p_{1d} + \gamma(p_{1r} + p_{2d} + p_{2r}) + \lambda_1\theta \quad (1)$$

$$D_{1r} = \alpha_{1d} - \beta p_{1r} + \gamma(p_{1d} + p_{2d} + p_{2r}) + \lambda_1\theta \quad (2)$$

$$D_{2d} = \alpha_{2d} - \beta p_{2d} + \gamma(p_{1r} + p_{1d} + p_{2r}) - \lambda_2\theta \quad (3)$$

$$D_{2r} = \alpha_{2r} - \beta p_{2r} + \gamma(p_{1r} + p_{2d} + p_{1d}) - \lambda_2\theta \quad (4)$$

The eco-friendly product (the green product) of the first manufacturer is an important factor stimulating demand for this product. Therefore, due to the increasing conscious of individuals and eco-friendly customers, the demand for non-green products is reduced. This assumption is considered in some studies (i.e. (Zhu and He, 2017)).

3.6 The profit functions for each player

The profit function for each player is provided in Eqs. (5)-(8). The cost of generating the green product is deducted from the first manufacturer's profit function. In Eq. (5), this cost $\boldsymbol{\mu\frac{\theta^2}{2}}$ is deducted.

$$\pi_{M1} = (w_1 - c_1)D_{1r} + (p_{1d} - c_1)D_{1d} - \mu\frac{\theta^2}{2} \quad (5)$$

$$\pi_{r1} = (p_{1r} - w_1)D_{1r} \quad (6)$$

$$\pi_{M2} = (w_2 - c_2)D_{2r} + (p_{2d} - c_2)D_{2d} \quad (7)$$

$$\pi_{r2} = (p_{2r} - w_2)D_{2r} \quad (8)$$

In centralized scenario total profit of SC_1 and SC_2 are provided in Eqs. (9) and (10), respectively.

$$\pi_{SC1} = \pi_{M1} + \pi_{R1} = (p_{1r} - c_1)D_{1r} + (p_{1d} - c_1)D_{1d} - \mu\frac{\theta^2}{2} \quad (9)$$

$$\pi_{SC2} = \pi_{M2} + \pi_{R2} = (p_{2r} - c_2)D_{2r} + (p_{2d} - c_2)D_{2d} \quad (10)$$

4. Game structure

4.1 The decentralized scenario

There are two supply chains that compete with each other. In addition, there is competition between the members of each supply chain. In other words, there is Nash competition between the retailers of the supply chains. In each supply chain, Stackelberg competition between the manufacturer and the retailer is established, in which the manufacturer plays the role of leader. Finally, Nash competition occurs between the manufacturers of the supply chains. The model for this problem is formulated in Eq. (11).

$$\begin{cases} \underset{p_{1d},\,\theta}{\text{Max}}\ \pi_{M_1} = D_{1r}(w_1 - c_1) + (p_{1d} - c_1)D_{1d} - \mu\dfrac{\theta^2}{2} \\ \underset{p_{2d}}{\text{Max}}\ \pi_{M_2} = D_{2r}(w_2 - c_2) + (p_{2d} - c_2)D_{2d} \\ \begin{cases} \underset{p_{1r}}{\text{Max}}\ \pi_{R_1} = D_{1r}(p_{1r} - w_1) \\ \underset{p_{2r}}{\text{Max}}\ \pi_{R_2} = D_{2r}(p_{2r} - w_2) \\ \pi_{R_1} > 0, \pi_{R_2} > 0, p_{ir} \geq w_i, \quad i \in I \end{cases} \end{cases} \tag{11}$$

First, a Nash equilibrium between the first and second retailers is obtained:

$$\begin{cases} \underset{p_{1r}}{\text{Max}}\ \pi_{R_1} = D_{1r}(p_{1r} - w_1) \\ \underset{p_{2r}}{\text{Max}}\ \pi_{R_2} = D_{2r}(p_{2r} - w_2) \\ \pi_{R_1} > 0, \pi_{R_2} > 0, p_{ir} \geq w_i, \quad i \in I \end{cases} \tag{12}$$

Lemma 1: The equilibrium prices obtained from the Nash equilibrium for the first and second retailers are calculated by Eqs. (13) and (14), respectively.

$$p_{1r} = \frac{2\beta\big(\alpha_{1r} + w_1\beta + (p_{1d} + p_{2d})\gamma + \theta\lambda_1\big) + \gamma\big(\alpha_{2r} + w_2\beta + (p_{1d} + p_{2d})\gamma - \theta\lambda_2\big)}{4\beta^2 - \gamma^2} \tag{13}$$

$$p_{2r} = \frac{2\alpha_{2r}\beta + 2w_2\beta^2 + \gamma(\alpha_{1r} + (2(p_{1d} + p_{2d}) + w_1)\beta + (p_{1d} + p_{2d})\gamma + \theta\lambda_1) - 2\beta\theta\lambda_2}{4\beta^2 - \gamma^2} \tag{14}$$

Proof. The second derivatives of the profit functions for the retailers are as follows:

$$\frac{d\pi_{R_i}^2}{d^2 p_{ir}} = -2\beta, \quad i \in I \tag{15}$$

It is obvious that the second derivatives of the profit functions for the retailers are negative. Therefore, in order to find the equilibrium points, the equation system derived by the first order derivatives (best solution functions), shown in Eqs. (16) and (17), is formed and solved.

$$\frac{d\pi_{R_1}}{dp_{1r}} = 0 \rightarrow \alpha_{1r} - p_{1r}\beta - (p_{1r} - w_1)\beta + (p_{1d} + p_{2d} + p_{2r})\gamma + \theta\lambda_1 = 0 \quad (16)$$

$$\frac{d\pi_{R_2}}{dp_{2r}} = 0 \rightarrow \alpha_{2r} - p_{2r}\beta - (p_{2r} - w_2)\beta + (p_{1d} + p_{1r} + p_{2d})\gamma - \theta\lambda_2 = 0 \quad (17)$$

The values of p_{1r} and p_{2r} are calculated by solving Eqs. (16) and (17). Thus, Lemma 1 is proven. □

Considering the competition between the retailer and the manufacturer of that product in each chain is Stackelberg, the optimal solution is obtained by placing prices. According to the Nash game in Proposition 1, in the profits of the retailers, the manufacturers' profit functions are obtained by Eqs. (18) and (19).

$$\pi_{M_1} = \frac{(w_1 - c_1)\beta Q_1}{4\beta^2 - \gamma^2} + \frac{(p_{1d} - c_1)(Q_2)}{2\beta - \gamma} - \frac{\theta^2\mu}{2} \quad (18)$$

$$\pi_{M_2} = \frac{(p_{2d} - c_2)Q_3}{2\beta - \gamma} + \frac{(W_2 - C_2)Q_4}{4\beta^2 - \gamma^2} \quad (19)$$

The values of Q_1 to Q_4 are shown in the appendix.

Theorem 1: In the Nash game, selling prices for the first and second manufacturers are from the first and second direct channels, and the green degree of products for manufacture 1, are obtained from Eqs. (20) and (22).

$$p_{1d} = \frac{(A_1 + \gamma^3(\lambda_1 + 4\lambda_2) - A_2(3\beta + \gamma) + A_3(2\beta - \gamma))}{Y} \quad (20)$$

$$p_{2d} = \frac{(B_1\lambda_1^2 + B_2\lambda_1\lambda_2 - B_3\gamma\lambda_2^2 + B_4 - B_5 - B_6)}{Y} \quad (21)$$

$$\theta = \frac{(C_1 + C_2 + C_3\gamma^5)(2\beta\lambda_1 - \gamma\lambda_2)}{Y} \quad (22)$$

The values of C_1 *to* C_3 , B_1 to B_6 , A_1 to A_3 and Y are shown in the appendix.

Proof: The Hessian matrix obtained from the profit function of the first manufacturer is defined as follows:

$$H(\pi_{M1}) = \begin{bmatrix} \frac{\partial^2 \pi_{M1}}{\partial {p_{1d}}^2} & \frac{\partial^2 \pi_{M1}}{\partial p_{1d} \partial_\theta} \\ \frac{\partial^2 \pi_{M1}}{\partial_\theta \partial p_{1d}} & \frac{\partial^2 \pi_{M1}}{\partial \theta^2} \end{bmatrix} = \begin{bmatrix} -\mu & \frac{2\beta\lambda_1 - \gamma\lambda_2}{2\beta - \gamma} \\ \frac{2\beta\lambda_1 - \gamma\lambda_2}{2\beta - \gamma} & -4\gamma + 2\beta(-5 - \frac{8\beta}{-2\beta + \gamma}) \end{bmatrix} \tag{23}$$

The Hessian matrix is negative definite, if the following two conditions are satisfied.

$\frac{\partial^2 \pi_{M1}}{\partial {p_{1d}}^2} < 0\,, \quad j \in J\,,$

$$\frac{\partial^2 \pi_{M1} \partial^2 \pi_{Mj}}{\partial {p_{1d}}^2 \ \partial \theta^2} - \left(\frac{\partial^2 \pi_{M1}}{\partial_\theta \partial p_{1d}}\right)^2 > 0\,, \quad j \in J$$

In order to meet the two conditions, the following equations must be established.

$$\mu > \frac{(-2\beta\lambda_1 + \gamma\lambda_2)^2}{8\beta^3 - 8\beta^2\gamma - 6\beta\gamma^2 + 4\gamma^3} \tag{24}$$

$$\beta > \frac{\gamma}{4} + \frac{\gamma}{4}\sqrt{17} \tag{25}$$

In order to maintain the concavity of the profit function for the first manufacturer, the conditions mentioned in Eqs. (24) and (25) are considered.

For the second manufacturer, the second order derivative can be calculated in Eq. (26).

$$\frac{d{\pi_{M_2}}^2}{d^2 p_{2d}} =- 2\beta \tag{26}$$

It is obvious that the second derivative of the profit function for the second manufacturer is negative.

In order to find the equilibrium points, the equation system derived by the first order derivatives, given in Eq. (27), is solved.

$$\begin{cases} \frac{d\pi_{M_1}}{d\theta} = 0 \\ \frac{d\pi_{M_1}}{dp_{1d}} = 0 \\ \frac{d\pi_{M_2}}{dp_{2d}} = 0 \end{cases} \tag{27}$$

Therefore, the values of p_{1d},p_{2d} and θ are obtained and the theorem 1 is proven. □

The values of p_{1r} and p_{2r} are obtained by placing p_{1d} and p_{2d} in Eqs. (13) and (14), which are shown in Eqs. (28) and (29).

$$p_{1r} = \frac{(E_1 + E_2 - E_3 + \mu(2\beta+\gamma)(4\beta^2 - 3\gamma^2)E_4 + \alpha_{1d}(2\beta+\gamma)E_5 + \alpha_{1r}(2\beta+\gamma)E_6)}{(2\beta+\gamma)Y}$$

$$p_{2r} = \left(\mathrm{F}_1 + \mathrm{F}_2 + \mathrm{F}_3 - \mathrm{F}_4 + \mathrm{F}_5 + \mathrm{F}_6 + \mathrm{F}_7 - \mathrm{F}_8 - 2c_2\gamma^6\lambda_2^2 - \gamma\mu(2\beta+\gamma)(4\beta^2 - 3\gamma^2)\mathrm{F}_9 + \beta w_2(2\beta+\gamma)\mathrm{F}_{10} + \alpha_{2r}(2\beta+\gamma)\mathrm{F}_{11}\right) / (2\beta+\gamma)Y$$

The values of E_1 *to* E_6 and F_1 *to* F_{11} are shown in the appendix.

4.2 The centralized scenario

As previously mentioned, in each supply-chain, members are integrated. Considering a competition between SC$_1$ and SC$_2$, A Nash game is established. The problem model is shown in Eq. (30).

$$\begin{cases} \max\limits_{\theta, p_{1r}, p_{1d}} \pi_{SC_1} = (p_{1r} - c_1)D_{1r} + (p_{1d} - c_1)D_{1d} - \mu\frac{\theta^2}{2} \\ \max\limits_{p_{2r}, p_{2d}} \pi_{SC_2} = (p_{2r} - c_2)D_{2r} + (p_{2d} - c_2)D_{2d} \\ \pi_{SC_1} > 0, \pi_{SC_2} > 0, p_{ir} \geq C_i, p_{id} \geq C_i \quad i \in I \end{cases} \tag{30}$$

Theorem 2: The equilibrium prices and green product degree obtained from the Nash equilibrium for the SC$_1$ and SC$_2$ are displayed in Eqs. (31)-(35).

$$p_{1d} = \frac{\mu H_1 - (\alpha_{1d} - \alpha_{1r} + 4c_1(\beta+\gamma))\lambda_1(\beta\lambda_1 - \gamma(\lambda_1 + \lambda_2))}{4(\beta+\gamma)(\gamma\lambda_1(\lambda_1+\lambda_2) + \beta^2\mu - \beta(\lambda_1^2 + 2\gamma\mu))} \tag{31}$$

$$p_{1r} = \frac{\mu \mathrm{H}_2 + (\alpha_{1d} - \alpha_{1r} - 4c_1(\beta+\gamma))\lambda_1(\beta\lambda_1 - \gamma(\lambda_1 + \lambda_2))}{4(\beta+\gamma)(\gamma\lambda_1(\lambda_1+\lambda_2) + \beta^2\mu - \beta(\lambda_1^2 + 2\gamma\mu))} \tag{32}$$

$$\theta = \frac{(\beta(\alpha_{1d} + \alpha_{1r} - 2c_1\beta) + (-\alpha_{1d} - \alpha_{1r} + \alpha_{2d} + \alpha_{2r} + 4c_1\beta + 2c_2\beta)\gamma + 2(c_1 - c_2)\gamma^2)\lambda_1}{2\lambda_1(-\beta\lambda_1 + \gamma(\lambda_1+\lambda_2)) + 2\beta(\beta - 2\gamma)\mu} \tag{33}$$

$$p_{2d} = \frac{(\lambda_1\mathrm{H}_3 + \mu\mathrm{H}_4)}{(4(\beta+\gamma)(\gamma\lambda_1(\lambda_1+\lambda_2) + \beta^2\mu - \beta(\lambda_1^2 + 2\gamma\mu)))} \tag{34}$$

$$p_{2r} = \frac{(\lambda_1 \mathrm{H}_5 + \mu \mathrm{H}_6)}{(4(\beta+\gamma)(\gamma\lambda_1(\lambda_1+\lambda_2) + \beta^2\mu - \beta(\lambda_1^2 + 2\gamma\mu)))} \quad (35)$$

The values of $H_1\ to\ H_6$ are shown in the appendix.

Proof: The Hessian matrix obtained from the profit function of the SC$_1$ is defined as follows:

$$H(\pi_{SC1}) = \begin{bmatrix} \frac{\partial^2 \pi_{SC1}}{\partial {p_{1d}}^2} & \frac{\partial^2 \pi_{SC1}}{\partial p_{1d} \partial p_{1r}} & \frac{\partial^2 \pi_{SC1}}{\partial p_{1d} \partial_\theta} \\ \frac{\partial^2 \pi_{SC1}}{\partial p_{1r} \partial p_{1d}} & \frac{\partial^2 \pi_{SC1}}{\partial {p_{1r}}^2} & \frac{\partial^2 \pi_{SC1}}{\partial p_{1r} \partial_\theta} \\ \frac{\partial^2 \pi_{SC1}}{\partial_\theta \partial p_{1d}} & \frac{\partial^2 \pi_{SC1}}{\partial_\theta \partial p_{1r}} & \frac{\partial^2 \pi_{SC1}}{\partial \theta^2} \end{bmatrix} = \begin{bmatrix} -2\beta & 2\gamma & \lambda_1 \\ 2\gamma & -2\beta & \lambda_1 \\ \lambda_1 & \lambda_1 & -\mu \end{bmatrix} \quad (36)$$

The leading principal minors are $M_1 = -2\beta,\ M_2 = 4\beta^2 - 4\gamma^2$ and $M_3 =- 4(\beta+\gamma)(-\lambda_1^2 + (\beta-\gamma)\mu)$. The Hessian matrix is negative definite if $M_1 < 0, M_2 > 0, M_3 < 0$. In order to meet the three mentioned conditions, the equation $\mu > \frac{\lambda_1^2}{\beta-\gamma}$ must be established. Therefore, the condition $\mu > \frac{\lambda_1^2}{\beta-\gamma}$ is considered to maintain the concavity of the profit function for SC$_1$.

Similarly, the Hessian matrix can be derived for profit function of SC$_2$ as follows:

$$H(\pi_{SC2}) = \begin{bmatrix} \frac{\partial^2 \pi_{SC2}}{\partial {p_{2d}}^2} & \frac{\partial^2 \pi_{SC2}}{\partial p_{2d} \partial p_{2r}} \\ \frac{\partial^2 \pi_{SC2}}{\partial p_{2r} \partial p_{2d}} & \frac{\partial^2 \pi_{SC2}}{\partial {p_{2r}}^2} \end{bmatrix} = \begin{bmatrix} -2\beta & 2\gamma \\ 2\gamma & -2\beta \end{bmatrix} \quad (37)$$

The Hessian matrix is negative definite if conditions $-2\beta < 0$ and $4\beta^2 - 4\gamma^2 > 0$ be established. It is obvious that the two conditions are satisfied, in other words, $\beta > 0$, $\beta > \gamma$. Therefore, the concavity of the profit function for SC$_2$ without new condition is established.

In order to find the equilibrium points, the equation system derived from the first order derivatives, given in Eq. (38), is solved.

$$\begin{cases}\frac{d\pi_{SC_1}}{dp_{1d}} = 0, \frac{d\pi_{SC_1}}{dp_{1r}} = 0, \frac{d\pi_{SC_1}}{d\theta} = 0, \frac{d\pi_{SC_2}}{dp_{2d}} = 0, \frac{d\pi_{SC_2}}{dp_{2r}} = 0\end{cases} \tag{38}$$

Therefore, the values of p_{1d},p_{1r} ,p_{2d},p_{2r} and θ are obtained and the theorem 2 is proven. □

5. Parametric sensitivity analysis

In this section, the effect of some parameters on the green degree is investigated. Sections 5.1 to 5.4 are relating to the decentralized model.

5.1 First manufacturer wholesale price effect on the green degree

From Eq. (39), which represents an equilibrium value for the green degree in the Nash equilibrium, the first derivative of θ with respect to parameter w_1 is derived. The value of this derivative is shown below.

$$\frac{d\theta}{dw_1} = \frac{J_1(2\beta\lambda_1 - \gamma\lambda_2)}{J_2(2\beta + \gamma)} \tag{39}$$

If the two conditions (40) and (41) are established, then $\frac{d\theta}{dw_1} > 0$.

$$\mu < \frac{(2\beta\lambda_1 - \gamma\lambda_2)(J_3)}{(2\beta - \gamma)(4\beta^2 - 4\beta\gamma - 5\gamma^2)(4\beta^2 - 3\gamma^2)} \tag{40}$$

$$\gamma + \sqrt{6}\gamma > 2\beta \tag{41}$$

According to Eq (39), parameter w_1 has a direct effect on θ, If Eq. (40) and (41) are established, increasing the wholesale price leads to increases in the green degree.

5.2 Second manufacturer wholesale price effect on the green degree

Eq. (42) is provided by the first order derivatives from Eq. (22) with respect to w_2 .

$$\frac{d\theta}{dw_2} = \frac{J_4(2\beta\lambda_1 - \gamma\lambda_2)}{J_2(2\beta + \gamma)} \tag{42}$$

If condition (43) and (44) are satisfied, then $\frac{d\theta}{dw_2} > 0$ and parameter w_2 has a positive effect on θ; means increasing θ leads to an increase in w_2 .

$$\mu > \frac{(2\beta\lambda_1 - \gamma\lambda_2)(J_3)}{(2\beta - \gamma)(4\beta^2 - 4\beta\gamma - 5\gamma^2)(4\beta^2 - 3\gamma^2)} \tag{43}$$

$$2\beta > \gamma + \sqrt{6}\gamma \tag{44}$$

5.3 Effect of the first manufacturer's production cost on the green degree

The first order derivative of θ with respect to c_1 is shown in Eq. (45).

$$\frac{d\theta}{dc_1} = \frac{J_5(2\beta\lambda_1 - \gamma\lambda_2)}{J_2(2\beta + \gamma)} \tag{45}$$

By satisfying condition (46) and (47), the first order derivative of θ with respect to c_1 will be greater than zero; thus, there is an increase in θ as C_1 increases.

$$\mu < \frac{(2\beta\lambda_1 - \gamma\lambda_2)(J_3)}{(2\beta - \gamma)(4\beta^2 - 4\beta\gamma - 5\gamma^2)(4\beta^2 - 3\gamma^2)} \tag{46}$$

$$\gamma + \sqrt{6}\gamma > 2\beta \tag{47}$$

5.4 Effect of the second manufacturer's production cost on the green degree

Eq. (48) has been provided by the first order derivatives from Eq. (22) with respect to C_2 .

$$\frac{d\theta}{dc_2} = \frac{J_6(2\beta\lambda_1 - \gamma\lambda_2)}{J_2(2\beta + \gamma)} \tag{48}$$

By satisfying condition (49) and (50), then $\frac{d\theta}{dc_2} > 0$, thus there is an increase in θ as C_2 increases.

$$\mu > \frac{(2\beta\lambda_1 - \gamma\lambda_2)(J_3)}{(2\beta - \gamma)(4\beta^2 - 4\beta\gamma - 5\gamma^2)(4\beta^2 - 3\gamma^2)} \tag{49}$$

$$2\beta > \gamma + \sqrt{6}\gamma \tag{50}$$

That values of J_1 to J_6 are provided in the appendix.

Regarding the relations presented in Sections 5.1-5.4, the following corollaries and insights can be derived.

Corollary 1. If the value of the cost-coefficient of the green degree (μ) is as small as possible, and also the value of the cross-price coefficient, i.e., (γ), is greater than $\gamma > 0.58\,\beta$, then increasing the wholesale price (w_1) and the manufacturing cost (c_1) in the first supply chain leads to increases in the green degree of the product (θ).

Insight 1. It can be stated that to increase the green degree of the product, the manufacturer that procures the green product can set a higher wholesale price for customers.

Corollary 2. If the value of the cost-coefficient of the green degree (μ) is as large as possible, and also the value of the cross-price coefficient, i.e. (γ), is lower than $\gamma < 0.58\,\beta$, increasing the wholesale price (w_2) and the manufacturing cost (c_2) in the second supply chain leads to increases in the green degree of the product (θ).

Insight 2. Because the manufacturer that produces the green product is not able to increase the wholesale price (w_1) and manufacturing cost (c_1), they can increase the green degree of their products, if the manufacturer related to the second supply chain increases their wholesale price (w_2) and manufacturing cost (c_2).

5.5 Effect of the λ_1 on the green degree in the centralized Scenario

In the centralized model, the first order derivative of θ with respect to λ_1 is shown in Eq (51).

$$\frac{d\theta}{d\lambda_1} = \frac{\beta(\alpha_{1d} + \alpha_{1r} - 2c_1\beta) + L_3\gamma + 2(c_1 - c_2)\gamma^2}{2\lambda_1(-\beta\lambda_1 + \gamma(\lambda_1 + \lambda_2)) + 2\beta(\beta - 2\gamma)\mu} + \frac{(\lambda_1 L_1 L_2)}{(2\lambda_1(-\beta\lambda_1 + \gamma(\lambda_1 + \lambda_2)) + 2\beta(\beta - 2\gamma)\mu)^2} \tag{51}$$

By satisfying condition (52), then $\frac{d\theta}{d\lambda_1} > 0$, thus there is an increase in θ as λ_1 increases.

$$\beta > \left(1 + \frac{\lambda_1}{\lambda_2}\right)\gamma, \mu > \frac{\lambda_1^2}{\beta - \gamma} \tag{52}$$

The values of L_1 and L_2 are shown in the appendix.

Corollary 3. With considering $\lambda_1 > \lambda_2$ and simplifying the relation $\beta > \left(1 + \frac{\lambda_1}{\lambda_2}\right)\gamma$, it is derivate that if the self-price is more than twice of the cross-price, λ_1 have a positive influence on the equilibrium green degree.

6. Results and insights

In this section, a numerical example is provided to illustrate the feasibility of the proposed problem solution. Parameter values are set based on the problem assumptions.

Table 1 shows the parameter values for the numerical example.

Table 1: Value of parameters

Parameter	Value	Parameter	Value
$(\alpha_{1r}, \alpha_{2r})$	(1200, 1000)	$(\alpha_{1d}, \alpha_{2d})$	(2000,1500)
(β, γ, μ)	(0.08, 0.02, 0.1)	(λ_1, λ_2)	(0.03, 0.025)
(c_1, c_2)	(1200, 1100)	(w_1, w_2)	(2000, 1500)

By setting the parameter values in the model and execution, the variable values and profit functions of the member of each supply chain are obtained. These values are shown in Table 2.

Table 2: Equilibrium value of variables

Variables	Value	
	Decentralized Model	Centralized Model
p_{1d}	20455.9	24367.3
p_{1r}	15705	20367.3
θ	6023.53	12700.4
p_{2d}	15617.4	17026.5
p_{2r}	12531.1	14526.5

As it is shown in Table 2, the value obtained from the centralized model for all variables is more than the decentralized model. As well, in the decentralized model, the values of profit functions are $\pi_{M_1} = 26431400, \pi_{r_1} = 15026100, \pi_{M_2} = 15942700$ and $\pi_{r_2} = 9734830$. Therefore, it is obvious that $\pi_{SC_1}^{DC} = \pi_{M_1} + \pi_{r_1} = 41457500$ and $\pi_{SC_2}^{DC} = \pi_{M_2} + \pi_{r_2} = 25677530$. In the centralized model, the value of profit function for supply chains are $\pi_{SC_1}^{C} = 46501400$ and $\pi_{SC_2}^{C} = 26160500$. Total profit for SC_1 and SC_2 in the centralized model is more than the decentralized model, in other words, $\pi_{SC_1}^{C} > \pi_{SC_1}^{DC}$ and $\pi_{SC_2}^{C} > \pi_{SC_2}^{DC}$.

According to the results of Table 2 and the above description, the following result are obtained.

Corollary 4. According to the comparison of the two scenarios, the degree of greenness of the product in centralized model is twice as many as the decentralized model. Also, the sales prices of both products are higher in centralized model. Therefore, the cooperation of the members of each supply chain will increase profits and increase the sustainability of the supply chain.

All result discussed in Sections 6.16.1 to 6.6 is relating to the decentralized scenario.

6.1 The effect of μ and β on the players' profit functions

The effect of the self-price coefficient and green cost on profit functions is shown in Fig. 2 and Fig. 3.

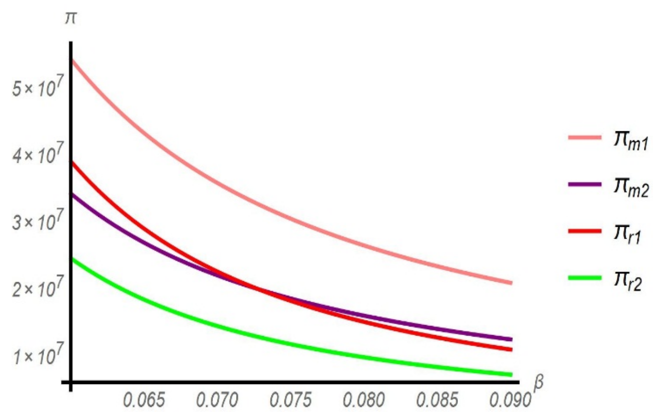

Fig. 2. Effect of self-price on profit functions

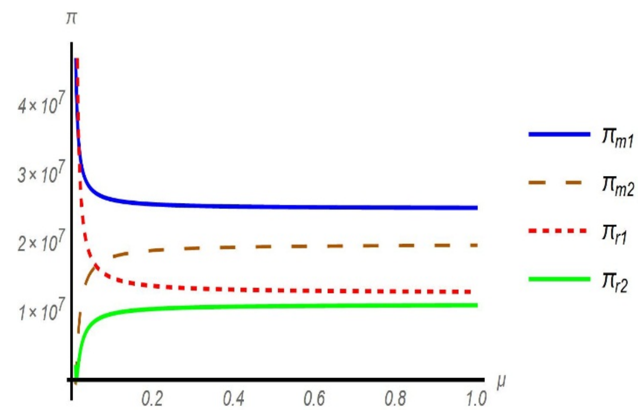

Fig. 3. Effect of green cost coefficient changes on profit functions

Corollary 5. Price sensitivity factor β is set at between 0.06 and 0.09 in Fig. 2, which shows that the second producer's profit is less than that of the first retailer in the beginning. As price sensitivity factor β increases, the second producer's profit increases more than that of the first retailer. At first, relation ($\pi_{M1} > \pi_{R1} > \pi_{M2} > \pi_{R2}$) is established between the value of players' profits, but increases in price sensitivity factor ($\beta \in [0.07, 0.075]$) creates the relation ($\pi_{M1} > \pi_{M2} > \pi_{R1} > \pi_{R2}$).

Corollary 6. Green cost coefficient μ is set at between 0 and 1 in Fig. 3. When the green cost coefficient increases, the profits of all the members of the supply chain that does not sell green products increase. In addition, the profits of all the members of the other supply chain decrease which is similar to the result reported by (Basiri and Heydari, 2017; Li et al., 2016). If changes in the profit functions for all players in the two supply chains are closer to a value of 1 for μ, the value is constant. If the first manufacturer can generate the commodity at the lowest green cost coefficient μ, then profits for vendors of the green product are at the maximum. In addition, the relation ($\pi_{M1} > \pi_{R1} > \pi_{M2} > \pi_{R2}$) changes to ($\pi_{M1} > \pi_{M2} > \pi_{R1} > \pi_{R2}$) with increases in the value of μ.

According to Corollary 5 and Corollary 6, insight 3 can be obtained.

Insight 3. If self-price increases, the profits of the manufacturers and the retailers will be reduced. The profit of first manufacturer and retailer decreases with increasing value of green cost, coefficient μ. The profit of the second manufacturer and retailer increases.

6.2 Effect of γ and β on players' profit functions

Fig. 4 and Fig. 5 shows the effect of the self-price coefficient and cross-price coefficient.

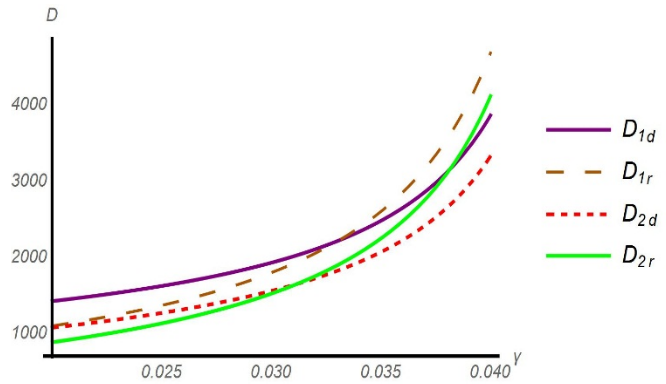

Fig. 4. Effect of cross-price coefficient on demand functions

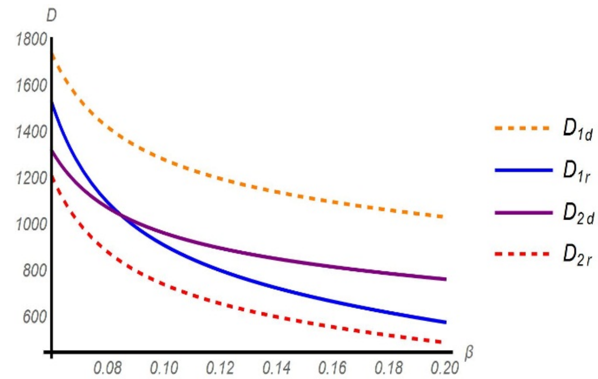

Fig. 5. Effect of self-price coefficient on demand functions

Corollary 7. As the factor cross-price sensitivity γ increases, there is more demand in the retail channels in comparison with the direct channels. Demand for the green product in the direct channel is highest when the value of cross-price sensitivity γ is at its lowest. If cross-price sensitivity γ increases, demand for the green and non-green product through the direct channels increases more than for the traditional channels (retailer channel). Demand for the green product is always higher than for the non-green product. Increasing cross-price sensitivity γ does not increase the demand for the non-green product compared with demand for the green product. In other words, increasing cross-price sensitivity γ only causes customers to change their shopping channels from the direct channels to the retailer channels.

Corollary 8. Fig. 5 shows that if price sensitivity factor β increases, there is more demand for the second direct channel than the first retailer channel. In addition, when price sensitivity coefficient β rises, the demand through the direct channels is more than the retailer channels. Based on the range of changes in self-price, the green product demand through the direct channel is always at its highest, and the non-green product demand through the retailer channel is at its lowest.

Similarly, insight 4 can be derived from Corollary 7 and Corollary 8.

Insight 4. Self-price β and cross-price γ have inverse effects on the demand functions. Increasing β reduces the demand function, and increasing γ increases the demand function.

6.3 Effect of γ and β on sale price

The effect β and γ on the product prices of the supply-chain players is shown in Fig. 6 and Fig. 7.

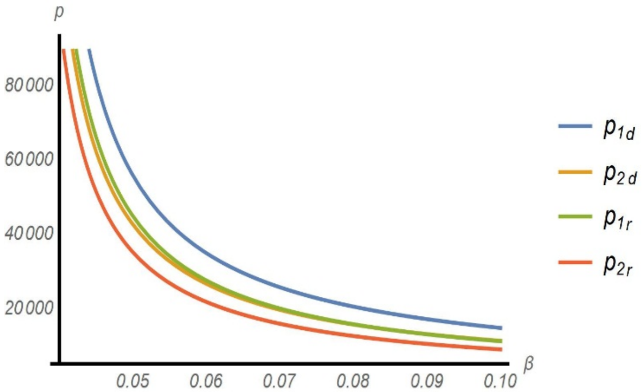

Fig. 6. Effect self-price coefficient on the product price of the supply-chain players

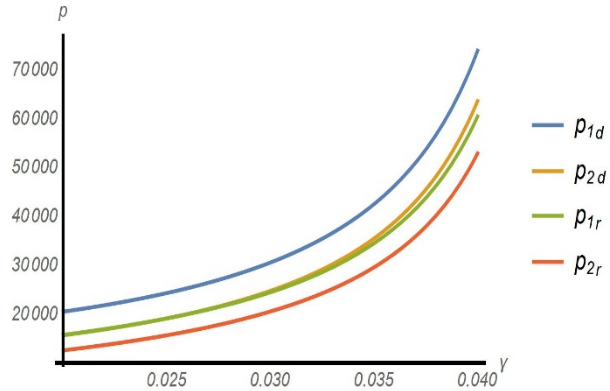

Fig. 7. Effect coefficient cross-price on the product price of the supply-chain players

Corollary 9. As shown in Fig. 6, decreasing the self-price sensitivity factor for the second manufacturer's direct channel and the first retailer leads to final sales prices that are about equal.

Corollary 10. According to Fig. 7, increasing the cross-price sensitivity factor for the second manufacturer's direct channel and the first retailer leads to final sale prices that are about equal.

A point to be noticed is that in both Fig. 6 and Fig. 7, the values of p_{2d} and p_{1r} overlap.

Based on Corollary 9 and Corollary 10, we can obtain insight 5.

Insight 5. Self-price β and cross-price γ have inverse effects on optimal prices. Increasing β reduces the optimal prices, and increasing γ increases the optimal prices.

6.4 Simultaneous effects of (μ and w_1) and (γ and β) on the first manufacturer profit function

Fig. 8 and Fig. 9 shows the simultaneous effects of (w_1, μ) and (β, γ) on first manufacturer's profit function.

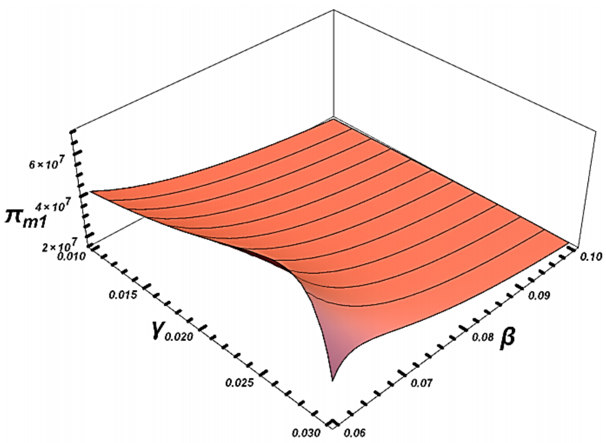

Fig. 8. The simultaneous effect of β and γ on first manufacture's profit function

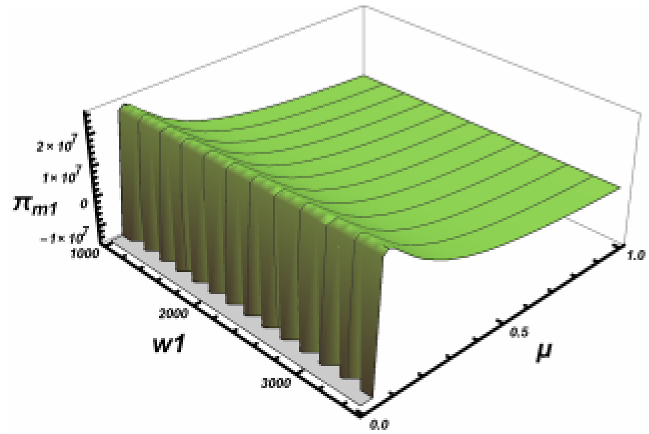

Fig. 9. The simultaneous effect of w_1 and μ on first manufacture's profit function

Corollary 11. Since γ has the maximum and β has the minimum value, the first manufacturer's profit is at its lowest. If the manufacturer wants to maximize its profits, γ should be set between 0.02 and 0.03 and β at the minimum value.

Corollary 12. Changes in the cost-coefficient of green degree and the first producer's wholesale price are shown together in Fig. 9. If μ is set at between 0.01 and 0.3, the first manufacturer's profit is at its maximum. Therefore, if the first manufacturer wants to reach the highest profit, it must to keep μ at its lowest value which is conforming with the result of (Li et al., 2016).The cost-coefficient of green degree μ is an important factor in determining profit.

By analysis of Corollary 11 and Corollary 12, insight 6 is obtained.

Insight 6. The manufacturer of the green product (the first manufacturer) can achieve higher profit by holding down the cost-coefficient of green degree μ and increasing the sensitivity coefficient of the green degree per unit product on demand λ_1.

6.5 Simultaneous effects of ($\lambda_1$and λ_2) and (μ and γ) on the second manufacturer's profit function

Fig. 10 shows the simultaneous effects of changes in each manufacturer's product green sensitivity factor (λ_1, λ_2) on the second manufacturer. Furthermore, the simultaneous effects (β, γ) on the second manufacturer's profit function is shown in Fig. 11.

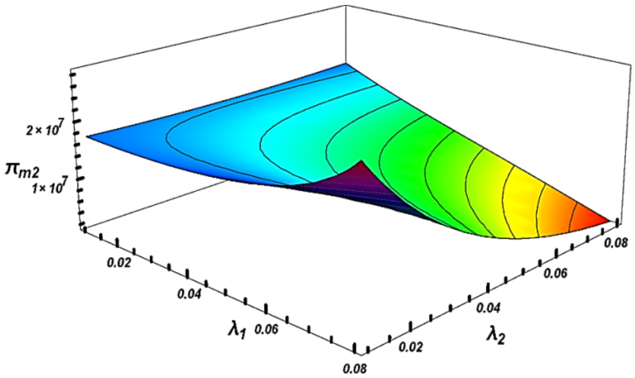

Fig. 10. The simultaneous effect of $\boldsymbol{\lambda_1}$ and $\boldsymbol{\lambda_2}$ on second manufacturer's profit function

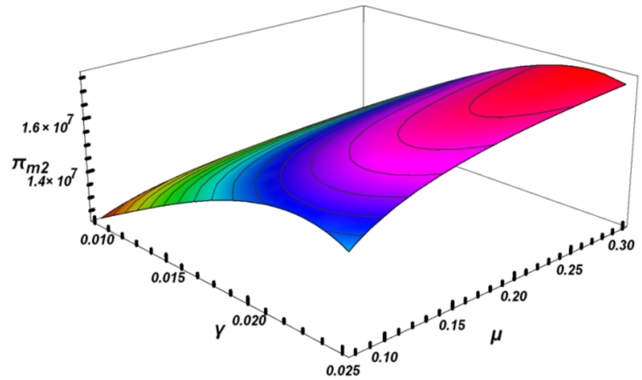

Fig. 11. The simultaneous effect of $\boldsymbol{\mu}$ and $\boldsymbol{\beta}$ on second manufacturer's profit function

Corollary 13. When λ_1 is at its maximum value and λ_2 is at its minimum value, the second manufacturer profit at the highest amount. In addition, when λ_1 is at its maximum and λ_2 is at its maximum value, the second manufacturer's profit is at its lowest amount. In both cases, when $\lambda_1 = \lambda_2 = 0.01$ or $\lambda_1 = 0.01, \lambda_2 = 0.08$, the profit is the same.

Corollary 14. Fig. 11 shows that as γ and μ reach their highest values, the second manufacturer's profit reaches its highest amount.

According to Corollary 13 and Corollary 14, insight 7 can be obtained.

Insight 7. The second manufacturer can achieve higher profit by increasing the green cost coefficient μ and the cross-price γ.

6.6 Simultaneous effects of ($\boldsymbol{\lambda_1}$ and $\boldsymbol{\mu}$) and ($\boldsymbol{\mu}$ and $\boldsymbol{\beta}$) on the green degree of the product

In Fig. 12 and Fig. 13, the simultaneous effects of (λ_1 , μ) and (μ , β) on the green degree of the first manufacture's product are shown.

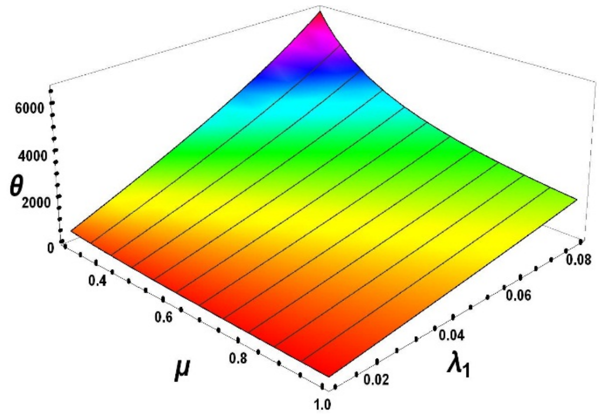

Fig. 12. The simultaneous effect of $\boldsymbol{\lambda_1}$ and $\boldsymbol{\mu}$ on the green degree of the first manufacture's product

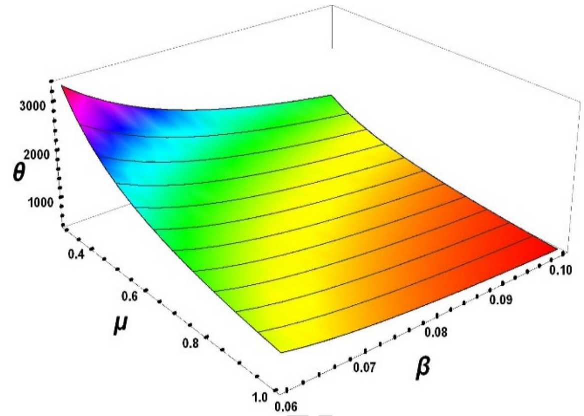

Fig. 13. The simultaneous effect of $\boldsymbol{\mu}$ and β on the green degree of the first manufacture's product

Corollary 15. In Fig. 12, if λ_1 is at its maximum value and μ is at its minimum value, the green degree of the first manufacture's product would be at the highest amount. In addition, the green degree of the first manufacture's product would be the least, if μ is at its maximum value and λ_1 is at its minimum value. When comparing the green degree of the first manufacture's product when (λ_1 , μ) are at their maximum with that of the (λ_1 , μ) at its minimum value, the first point is evidently higher than the second one. In other words, $\boldsymbol{\theta}_{\lambda_1^{max},\mu^{max}} > \boldsymbol{\theta}_{\lambda_1^{min},\mu^{min}}$.

Corollary 16. Fig. 13, shows that as β and μ place in their lowest values, the green degree of the first manufacture's product reaches its highest amount. Increasing μ cause reduction in the green degree which is consistent with the result presented by (Li et al., 2016).

Insight 8. In fact, reducing the cost-coefficient of green degree is not possible, in order to increase the degree of green products, manufacturers should increase public awareness to have more demand of the product.

6.7 Comparing the green degree of product in two Scenarios

Simultaneous effects of (μ , β) on the green degree of the first manufacture's product are evaluated in both scenarios. As it is shown in Fig. 14, the equilibrium green degree value in the centralized scenario is more than in the decentralized one.

Insight 9. One way to increase the green degree for governments is a codification of such rules in order to cooperation among the members of the supply chain.

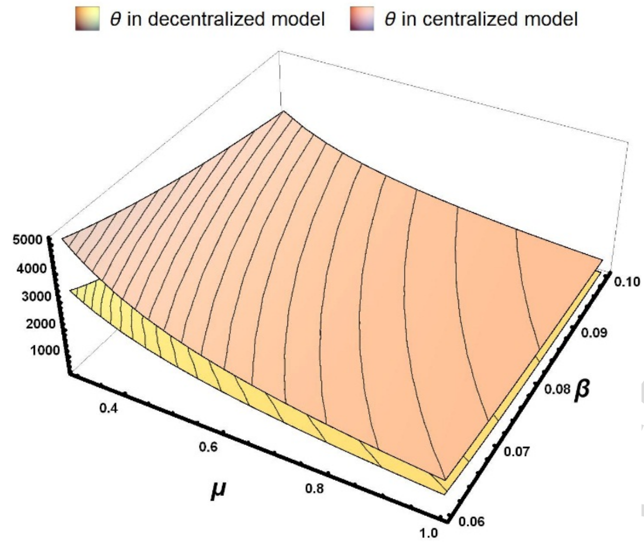

Fig. 14. Comparing the green degree in two scenarios

7. Conclusions and suggestions for future research

Given the environmental concerns, the production of green products has grown today. Also, improvements in people's knowledge in society have led them to buy more green products. So manufacturers are looking to produce green products to attract eco-friendly customers and address environmental concerns. Providing green products is a competitive advantage in the supply chain. Also, making optimal decisions for green product manufacturers and analyzing the competitive conditions of the market is necessary. Therefore, this paper discusses sales of green and non-green products by two manufacturers in dual distribution channels. There is competition between manufacturers and retailers in selling products. Pricing strategies and green degrees of products are discussed, and equilibrium decisions for players in both supply chains are studied.

This problem is solved under two different scenarios: centralized and decentralized. Each of the scenarios was evaluated with parametric analyzes and numerical examples. The numerical results show that in the centralized model, in addition to making more profit, green products can be produced with a higher degree of greenness. Therefore, we have a greener supply chain with collaboration model. Other result show that the green degree increases with increases in the wholesale prices and the manufacturers' costs under special conditions, which are inverse for the first and the second manufacturer. In addition, to increase the degree of green product, if the first manufacturer is not able to reduce his cost-coefficient of green degree, increasing public awareness should be increased so as to people are encouraged to buy green products. Therefore, noticing people about buying green products should be given special attention.

For future research, governments can play a very important and crucial role in improvement of sustainability in supply chains and in society. They can increase demand for green products by increasing public awareness and subsidies on the purchase of green products. One way to increase the degree green of product is to establish regulation by governments relating to cooperation among supply chain members. One direction for further research is to add government to the problem and investigate the effect of its presence. Another approach is to add, demand functions as uncertain variables; they could be considered as having probability functions following fuzzy set theory. It could be assume that demand function is not linear and has non-linear functions. Also, as important members of supply chains, suppliers could be considered in their role as providers of safe and recyclable materials.

Appendix

$$A_1 = w_1\beta(2\beta\lambda_1 - \gamma\lambda_2)(8\beta^3\lambda_1 - 6\beta\gamma^2\lambda_1 - 4\beta^2\gamma(\lambda_1 + 2\lambda_2)$$

$$A_2 = c_1(2\beta\lambda_1 - \gamma\lambda_2)(8\beta^3\lambda_1 - 6\beta\gamma^2\lambda_1 - 4\beta^2\gamma(\lambda_1 + 2\lambda_2) + \gamma^3(\lambda_1 + 4\lambda_2))$$

$$A_3 = 4c_1(2\beta + \gamma)(2\beta^2 - \beta\gamma - 2\gamma^2)(\beta^2 - \beta\gamma - \gamma^2)\mu$$

$$A_4 = (4\beta^2 - \gamma^2)(8\alpha_{1d}\beta^3 + 4\beta^2(- 2\alpha_{1d} + \alpha_{1r} + \alpha_{2d} + \alpha_{2r} + (c_2 + 2w_1 + w_2)\beta)\gamma - 2\beta(3\alpha_{1d} + (c_2 + w_1 - w_2)\beta)\gamma^2 + (4\alpha_{1d} - 3\alpha_{1r} - \alpha_{2d} - 3\alpha_{2r} - (6c_2 + 7w_1 + 2w_2)\beta)\gamma^3 - 2c_2\gamma^4)\mu$$

$$B_1 =- 40\beta^4\gamma c_1 - 20\beta^3\gamma^2c_1 + 12\beta^2\gamma^3c_1 + 4\beta\gamma^4c_1 + 8\beta^4\gamma w_1 + 4\beta^3\gamma^2w_1 - 4\beta^2\gamma^3w_1 - 16\beta^4\gamma w_2 - 4\beta^3\gamma^2w_2 + 2\beta^2\gamma^3w_2 + 8\beta^3\gamma\alpha_d - 2\beta\gamma^3\alpha_d - 8\beta^3\gamma\alpha_r + 2\beta\gamma^3\alpha_r - 8\beta^3\gamma\alpha_{2r} + 2\beta\gamma^3\alpha_{2r}$$

$$B_2 =- 32\beta^5c_1 - 12\beta^2\gamma^3c_1 + 4\beta\gamma^4c_1 + 2\gamma^5c_1 + 16\beta^5w_1 + 8\beta^4\gamma w_1 - 4\beta^3\gamma^2w_1 + 2\beta^2\gamma^3w_1 - 2\beta\gamma^4w_1 + 8\beta^4\gamma w_2 - 12\beta^3\gamma^2w_2 - 6\beta^2\gamma^3w_2 + \beta\gamma^4w_2 + 16\beta^4\alpha_d - \gamma^4\alpha_d + 8\beta^3\gamma\alpha_r - 4\beta^2\gamma^2\alpha_r - 2\beta\gamma^3\alpha_r + \gamma^4\alpha_r + 8\beta^3\gamma\alpha_{2r} - 4\beta^2\gamma^2\alpha_{2r} - 2\beta\gamma^3\alpha_{2r} + \gamma^4\alpha_{2r}$$

$$B_3 = 16\beta^4c_1 - 10\beta^2\gamma^2c_1 + \beta\gamma^3c_1 + \gamma^4c_1 - 8\beta^4w_1 - 4\beta^3\gamma w_1 + 4\beta^2\gamma^2w_1 - 4\beta^3\gamma w_2 + 2\beta^2\gamma^2w_2 + 2\beta\gamma^3w_2 - 8\beta^3\alpha_d + 2\beta\gamma^2\alpha_d - 4\beta^2\gamma\alpha_r + \gamma^3\alpha_r - 4\beta^2\gamma\alpha_{2r} + \gamma^3\alpha_{2r}$$

$$B_4 = \alpha_{2d}(4\beta^2 - \gamma^2)(- 2\beta\lambda_1 + \gamma\lambda_2)^2 - 2\alpha_{2d}(- 2\beta + \gamma)^2(4\beta^3 - 5\beta\gamma^2 - 2\gamma^3)\mu$$

$$B_5 =- \gamma(- 4\beta^2 + \gamma^2)(- 4\beta^2(\alpha_{1d} + \alpha_{1r} + \alpha_{2r} + (c_1 + w_1 + 2w_2)\beta) + 2(c_1 - w_1 + w_2)\beta^2\gamma + (\alpha_{1d} + 3(\alpha_{1r} + \alpha_{2r}) + (6c_1 + 2w_1 + 7w_2)\beta)\gamma^2 + 2c_1\gamma^3)\mu$$

$$B_6 =- 2c_2(2\beta + \gamma)(\beta^2 - \beta\gamma - \gamma^2)(- (- 2\beta\lambda_1 + \gamma\lambda_2)^2 + 2(4\beta^3 - 4\beta^2\gamma - 3\beta\gamma^2 + 2\gamma^3)\mu)$$

$$C_1 = 16\beta^4(\alpha_{1d} + (- 2c_1 + w_1)\beta) + 8\beta^3(- \alpha_{1d} + \alpha_{1r} + \alpha_{2d} + \alpha_{2r} + (2c_1 + c_2 + w_2)\beta)\gamma$$

$$C_2 = 4\beta^2(- 5\alpha_{1d} + \alpha_{1r} + \alpha_{2d} + \alpha_{2r} + 19c_1\beta - 7w_1\beta + 2w_2\beta)\gamma^2 + 2\beta(\alpha_{1d} - 3\alpha_{1r} - \alpha_{2d} - 3\alpha_{2r} + (4c_1 - 7c_2 - 2w_1 - w_2)\beta)\gamma^3$$

$$C_3 = (4\alpha_{1d} - 3\alpha_{1r} - \alpha_{2d} - 3\alpha_{2r} - (29c_1 + 10c_2 - 8w_1 + 2w_2)\beta)\gamma^4 - (7c_1 + 2c_2)$$

$E_1 = -64c_1\beta^6\lambda_1^2 - 48c_1\beta^5\gamma\lambda_1^2 + 16w_1\beta^5\gamma\lambda_1^2 + 72c_1\beta^4\gamma^2\lambda_1^2 - 8w_1\beta^4\gamma^2\lambda_1^2 + 60c_1\beta^3\gamma^3\lambda_1^2 - 12w_1\beta^3\gamma^3\lambda_1^2 + 2c_1\beta^2 \gamma^4\lambda_1^2$

$E_2 = 2w_1\beta^2\gamma^4\lambda_1^2 - 2c_1\beta\gamma^5\lambda_1^2 + 96c_1\beta^5\gamma\lambda_1\lambda_2 + 104c_1\beta^4\gamma^2\lambda_1\lambda_2 - 24w_1\beta^4\gamma^2\lambda_1\lambda_2 - 52c_1\beta^3\gamma^3\lambda_1\lambda_2 + 4w_1\beta^3\gamma^3\lambda_1\lambda_2 - 70c_1\beta^2\gamma^4\lambda_1\lambda_2 + 14w_1\beta^2\gamma^4\lambda_1\lambda_2$

$E_3 = 9c_1\beta\gamma^5\lambda_1\lambda_2 - w_1\beta\gamma^5\lambda_1\lambda_2 + c_1\gamma^6\lambda_1\lambda_2 - 32c_1\beta^4\gamma^2\lambda_2^2 - 40c_1\beta^3\gamma^3\lambda_2^2 + 8w_1\beta^3\gamma^3\lambda_2^2 + 8c_1\beta^2\gamma^4\lambda_2^2 + 20c_1\beta\gamma^5\lambda_2^2 - 4w_1\beta\gamma^5\lambda_2^2 + 4c_1\gamma^6\lambda_2^2$

$E_4 = 8w_1\beta^4 + 4\beta^2(\alpha_{2d} + \alpha_{2r} + (c_1 + c_2 - 2w_1 + w_2)\beta)\gamma - 2(c_1 + c_2 + 2w_1 - w_2)\beta^2\gamma^2 - (\alpha_{2d} + 3\alpha_{2r} + (6c_1 + 6c_2 - 3w_1 + 2w_2)\beta)\gamma^3 - 2(c_1 + c_2)\gamma^4$

$E_5 = -8\beta^3\gamma\lambda_1(\lambda_1 + 3\lambda_2) + 2\beta\gamma^3\lambda_1(\lambda_1 + 7\lambda_2) + 4\beta^2\gamma^2(-3\lambda_1^2 + \lambda_1\lambda_2 + 2\lambda_2^2 - 4\gamma\mu) + 16\beta^4(\lambda_1^2 + \gamma\mu) + \gamma^4(-\lambda_2 (\lambda_1 + 4\lambda_2) + 3\gamma\mu)$

$E_6 = 32\beta^5\mu + 8\beta^3\gamma(\lambda_1^2 + 3\lambda_1\lambda_2 - 6\gamma\mu) + \gamma^4(\lambda_2(\lambda_1 + 4\lambda_2) - 6\gamma\mu) - 16\beta^4(\lambda_1^2 + 2\gamma\mu) + 4\beta^2\gamma^2((\lambda_1 - \lambda_2)(3\lambda_1 + 2 \lambda_2) + 8\gamma\mu) + 2\beta\gamma^3(-\lambda_1(\lambda_1 + 7\lambda_2) + 9\gamma\mu)$

$\mathrm{F}_1 = 16\alpha_{1d}\beta^4\gamma\lambda_1^2 - 16\alpha_{1r}\beta^4\gamma\lambda_1^2 - 16\alpha_{2d}\beta^4\gamma\lambda_1^2 - 80c_1\beta^5\gamma\lambda_1^2 - 16c_2\beta^5\gamma\lambda_1^2 + 16w_1\beta^5\gamma\lambda_1^2 + 8\alpha_{1d}\beta^3\gamma^2\lambda_1^2 - 8\alpha_{1r}\beta^3 \gamma^2\lambda_1^2 - 8\alpha_{2d}\beta^3\gamma^2\lambda_1^2 - 80c_1\beta^4\gamma^2\lambda_1^2$

$\mathrm{F}_2 = 16w_1\beta^4\gamma^2\lambda_1^2 - 12\alpha_{1d}\beta^2\gamma^3\lambda_1^2 + 12\alpha_{1r}\beta^2\gamma^3\lambda_1^2 + 4\alpha_{2d}\beta^2\gamma^3\lambda_1^2 + 44c_1\beta^3\gamma^3\lambda_1^2 + 28c_2\beta^3\gamma^3\lambda_1^2 - 12w_1\beta^3\gamma^3\lambda_1^2 - 6 \alpha_{1d}\beta\gamma^4\lambda_1^2 + 6\alpha_{1r}\beta\gamma^4\lambda_1^2 + 2\alpha_{2d}\beta\gamma^4\lambda_1^2$

$\mathrm{F}_3 = 60c_1\beta^2\gamma^4\lambda_1^2 + 20c_2\beta^2\gamma^4\lambda_1^2 - 12w_1\beta^2\gamma^4\lambda_1^2 + 12c_1\beta\gamma^5\lambda_1^2 + 4c_2\beta\gamma^5\lambda_1^2 - 32\alpha_{1d}\beta^5\lambda_1\lambda_2 + 64c_1\beta^6\lambda_1\lambda_2 - 32w_1 \beta^6\lambda_1\lambda_2 - 16\alpha_{1d}\beta^4\gamma\lambda_1\lambda_2 - 16\alpha_{1r}\beta^4\gamma\lambda_1\lambda_2$

$\mathrm{F}_4 = 16\alpha_{2d}\beta^4\gamma\lambda_1\lambda_2 + 32c_1\beta^5\gamma\lambda_1\lambda_2 - 16c_2\beta^5\gamma\lambda_1\lambda_2 - 32w_1\beta^5\gamma\lambda_1\lambda_2 + 16\alpha_{1d}\beta^3\gamma^2\lambda_1\lambda_2 - 32c_1\beta^4\gamma^2\lambda_1\lambda_2 + 8c_2\beta^4 \gamma^2\lambda_1\lambda_2 + 16w_1\beta^4\gamma^2\lambda_1\lambda_2 + 8\alpha_{1d}\beta^2\gamma^3\lambda_1\lambda_2$

$\mathrm{F}_5 = 16\alpha_{1r}\beta^2\gamma^3\lambda_1\lambda_2 + 8\alpha_{2d}\beta^2\gamma^3\lambda_1\lambda_2 + 8c_1\beta^3\gamma^3\lambda_1\lambda_2 + 28c_2\beta^3\gamma^3\lambda_1\lambda_2 + 16w_1\beta^3\gamma^3\lambda_1\lambda_2 + 6\alpha_{1d}\beta\gamma^4\lambda_1\lambda_2 - 4c_1\beta^2 \gamma^4\lambda_1\lambda_2 + 6c_2\beta^2\gamma^4\lambda_1\lambda_2 + 6w_1\beta^2\gamma^4\lambda_1\lambda_2$

$\mathrm{F}_6 = 3\alpha_{1d}\gamma^5\lambda_1\lambda_2 - 3\alpha_{1r}\gamma^5\lambda_1\lambda_2 - \alpha_{2d}\gamma^5\lambda_1\lambda_2 - 24c_1\beta\gamma^5\lambda_1\lambda_2 - 6c_2\beta\gamma^5\lambda_1\lambda_2 + 6w_1\beta\gamma^5\lambda_1\lambda_2 - 6c_1\gamma^6\lambda_1\lambda_2 - 2c_2\gamma^6\lambda_1 \lambda_2 + 16\alpha_{1d}\beta^4\gamma\lambda_2^2 - 32c_1\beta^5\gamma\lambda_2^2 + 16w_1\beta^5\gamma\lambda_2^2$

$\mathrm{F}_7 = 8\alpha_{1d}\beta^3\gamma^2\lambda_2^2 + 8\alpha_{1r}\beta^3\gamma^2\lambda_2^2 + 8\alpha_{2d}\beta^3\gamma^2\lambda_2^2 - 16c_1\beta^4\gamma^2\lambda_2^2 + 8c_2\beta^4\gamma^2\lambda_2^2 + 16w_1\beta^4\gamma^2\lambda_2^2 - 12\alpha_{1d}\beta^2\gamma^3\lambda_2^2 + 4\alpha_{1r} \beta^2\gamma^3\lambda_2^2 + 4\alpha_{2d}\beta^2\gamma^3\lambda_2^2 + 36c_1\beta^3\gamma^3\lambda_2^2$

$\mathrm{F}_8 = 12w_1\beta^3\gamma^3\lambda_2^2 - 6\alpha_{1d}\beta\gamma^4\lambda_2^2 - 6\alpha_{1r}\beta\gamma^4\lambda_2^2 - 2\alpha_{2d}\beta\gamma^4\lambda_2^2 + 16c_1\beta^2\gamma^4\lambda_2^2 - 14c_2\beta^2\gamma^4\lambda_2^2 - 12w_1\beta^2\gamma^4\lambda_2^2 - 3\alpha_{1r}\gamma^5\lambda_2^2 - \alpha_{2d}\gamma^5\lambda_2^2 - 9c_1\beta\gamma^5\lambda_2^2 - 10c_2\beta\gamma^5\lambda_2^2 - 3c_1\gamma^6\lambda_2^2$

$\mathrm{F}_9 = -4\beta^2(\alpha_{1d} + \alpha_{1r} + \alpha_{2d} + (c_1 + c_2 + w_1)\beta) + 2(c_1 + c_2 - w_1)\beta^2\gamma + (\alpha_{1d} + 3\alpha_{1r} + \alpha_{2d} + 2(3(c_1 + c_2) + w_1)\beta)\gamma^2 + 2(c_1 + c_2)\gamma^3$

$F_{10} =-(2\beta+\gamma)\big(2\beta\lambda_1-\gamma\lambda_2\big)\big(4\beta^2\lambda_1-\gamma^2\big(\lambda_1-2\lambda_2\big)-2\beta\gamma\big(\lambda_1+\lambda_2\big)\big)+(2\beta-\gamma)\big(4\beta^2-3\gamma^2\big)\big(4\beta^2-2\beta\gamma-3\gamma^2\big)\mu$

$F_{11} = 32\beta^5\mu+\gamma^4\big(-2\lambda_1\lambda_2+\lambda_2^2-6\gamma\mu\big)+16\beta^3\gamma\big(\lambda_1\lambda_2-3\gamma\mu\big)-16\beta^4\big(\lambda_1^2+2\gamma\mu\big)+4\beta^2\gamma^2\big(3\lambda_1^2-\lambda_2^2+8\gamma\mu\big)+2\beta\gamma^3\big(2\lambda_1(\lambda_1-2\lambda_2)+9\gamma\mu\big)$

$H_1 = (2c_1(\beta-\gamma)^2(\beta+\gamma)+\alpha_{1d}(2\beta^2-2\beta\gamma-\gamma^2)+\gamma(\alpha_{1r}(2\beta-\gamma)+(\beta+\gamma)(\alpha_{2d}+\alpha_{2r}+2c_2\beta-2c_2\gamma)))$

$H_2 = (2c_1(\beta-\gamma)^2(\beta+\gamma)+\alpha_{1r}(2\beta^2-2\beta\gamma-\gamma^2)+\gamma(\alpha_{1d}(2\beta-\gamma)+(\beta+\gamma)(\alpha_{2d}+\alpha_{2r}+2c_2\beta-2c_2\gamma)))$

$H_3 = (-2(\alpha_{2d}\beta+\alpha_{2r}\gamma+(\beta+\gamma)(c_2(\beta-\gamma)+2c_1\gamma))\lambda_1-(\beta(\alpha_{1d}+\alpha_{1r}-2c_1\beta)+(\alpha_{1d}+\alpha_{1r}-\alpha_{2d}+\alpha_{2r})\gamma+2c_1\gamma^2)\lambda_2)$

$H_4 = (2\beta^2(\alpha_{2d}+c_2\beta)+\beta(\alpha_{1d}+\alpha_{1r}+2(-\alpha_{2d}+\alpha_{2r}+c_1\beta-c_2\beta))\gamma+(\alpha_{1d}+\alpha_{1r}-\alpha_{2d}-\alpha_{2r}-2c_2\beta)\gamma^2+2(-c_1+c_2)\gamma^3)$

$H_5 = (-2(\alpha_{2r}\beta+\alpha_{2d}\gamma+(\beta+\gamma)(c_2(\beta-\gamma)+2c_1\gamma))\lambda_1-(\beta(\alpha_{1d}+\alpha_{1r}-2c_1\beta)+(\alpha_{1d}+\alpha_{1r}+\alpha_{2d}-\alpha_{2r})\gamma+2c_1\gamma^2)\lambda_2)$

$H_6 = (2\beta^2(\alpha_{2r}+c_2\beta)+\beta(\alpha_{1d}+\alpha_{1r}+2(\alpha_{2d}-\alpha_{2r}+c_1\beta-c_2\beta))\gamma+(\alpha_{1d}+\alpha_{1r}-\alpha_{2d}-\alpha_{2r}-2c_2\beta)\gamma^2+2(-c_1+c_2)\gamma^3)$

$$L_1 = (\beta(\alpha_{1d}+\alpha_{1r}-2c_1\beta)+(-\alpha_{1d}-\alpha_{1r}+\alpha_{2d}+\alpha_{2r}+4c_1\beta+2c_2\beta)\gamma+2(c_1-c_2)\gamma^2)$$

$$L_2 = (2(-\beta+\gamma)\lambda_1+2(-\beta\lambda_1+\gamma(\lambda_1+\lambda_2)))$$

$$L_3 = (-\alpha_{1d}-\alpha_{1r}+\alpha_{2d}+\alpha_{2r}+4c_1\beta+2c_2\beta)$$

$$J_1 = 16\beta^5-28\beta^3\gamma^2-4\beta^2\gamma^3+8\beta\gamma^4$$

$J_2 = 32\beta^5\mu+\gamma^4\big(\lambda_2(\lambda_1+4\lambda_2)-15\gamma\mu\big)+8\beta^3\gamma\big(\lambda_1^2+3\lambda_1\lambda_2-6\gamma\mu\big)-16\beta^4\big(\lambda_1^2+3\gamma\mu\big)+2\beta\gamma^3(-\lambda_1(\lambda_1+7\lambda_2)+9\gamma\mu)+4\beta^2\gamma^2((\lambda_1-\lambda_2)(3\lambda_1+2\lambda_2)+14\gamma\mu)$

$$J_3 = 8\beta^3\lambda_1-6\beta\gamma^2\lambda_1-4\beta^2\gamma(\lambda_1+2\lambda_2)+\gamma^3(\lambda_1+4\lambda_2)$$

$$J_4 = 8\beta^4\gamma+8\beta^3\gamma^2-2\beta^2\gamma^3-2\beta\gamma^4$$

$$J_5 =-32\beta^5+16\beta^4\gamma+76\beta^3\gamma^2+8\beta^2\gamma^3-29\beta\gamma^4-7\gamma^5$$

$$J_6 = 8\beta^4\gamma-14\beta^2\gamma^3-10\beta\gamma^4-2\gamma^5$$

$$Q_1 = 2\alpha_{1r}\beta+\alpha_{2r}\gamma+2p_{1d}\beta\gamma+2p_{2d}\beta\gamma+w_2\beta\gamma+p_{1d}\gamma^2+p_{2d}\gamma^2+w_1\big(-2\beta^2+\gamma^2\big)+2\beta\theta\lambda_1-\gamma\theta\lambda_2$$

$$Q_2 = \alpha_{1d}(2\beta-\gamma)+\big(\alpha_{1r}+\alpha_{2r}\big)\gamma+2p_{2d}\beta\gamma+w_1\beta\gamma+w_2\beta\gamma+p_{2d}\gamma^2+p_{1d}\big(-2\beta^2+\beta\gamma+2\gamma^2\big)+2\beta\theta\lambda_1-\gamma\theta\lambda_2$$

$$Q_3 = \alpha_{2d}(2\beta-\gamma)+p_{2d}(-2\beta^2+\beta\gamma+2\gamma^2)+\gamma(\alpha_{1r}+\alpha_{2r}+(2p_{1d}+w_1+w_2)\beta+p_{1d}\gamma+\theta\lambda_1)-2\beta\theta\lambda_2$$

$$Q_4 = \beta(2\alpha_{2r}\beta+w_2(-2\beta^2+\gamma^2)+\gamma(\alpha_{1r}+(2(p_{1d}+p_{2d})+w_1)\beta+(p_{1d}+p_{2d})\gamma+\theta\lambda_1)-2\beta\theta\lambda_2)$$

$$Y = (2\beta + \gamma)(32\beta^5\mu + \gamma^4(\lambda_2(\lambda_1 + 4\lambda_2) - 15\gamma\mu) + 8\beta^3\gamma(\lambda_1^2 + 3\lambda_1\lambda_2 - 6\gamma\mu) - 16\beta^4(\lambda_1^2 + 3\gamma\mu) + 2\beta\gamma^3(-\lambda_1(\lambda_1 + 7\lambda_2) + 9\gamma\mu) + 4\beta^2\gamma^2((\lambda_1 - \lambda_2)(3\lambda_1 + 2\lambda_2) + 14\gamma\mu))$$

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