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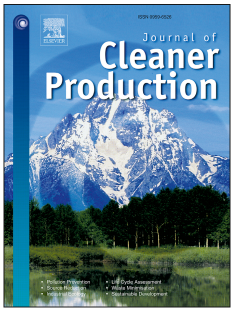

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A Game Theoretical for Coordination of Pricing, Recycling, and Green Product Decisions in the Supply Chain

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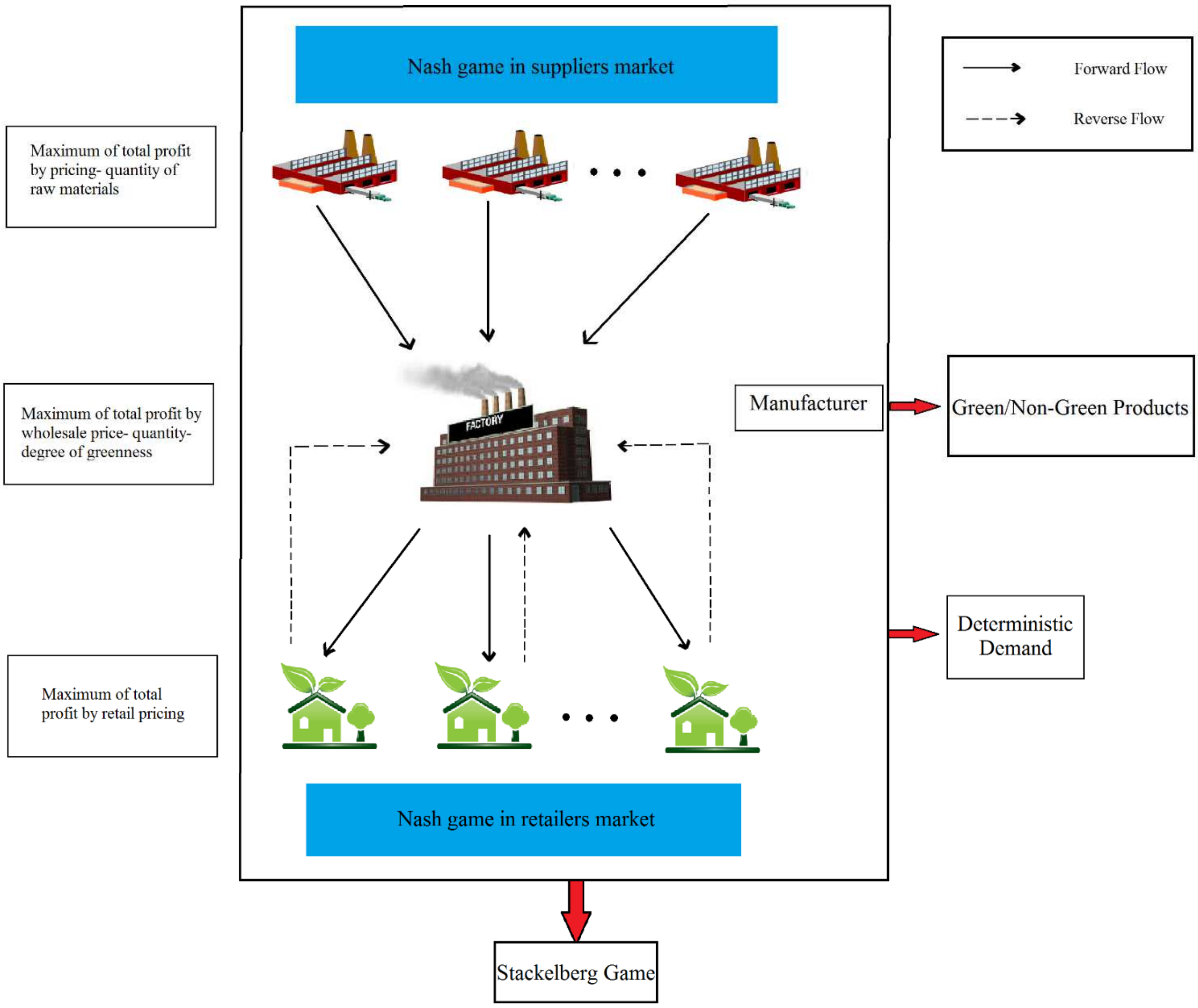
Grafical abstract



A GAME THEORETICAL FOR COORDINATION OF PRICING, RECYCLING, AND GREEN PRODUCT DECISIONS IN THE SUPPLY CHAIN

Abstract

In order to increase profit of supply chain there are many powerful coordination tools such as: pricing, advertising, inventory management products and etc. Also, nowadays green products paid attention to the manufacturers, therefore effort has been made in this paper to study, through the non-cooperative game theory, a multi-product competitive 3-echelon supply chain with a specified demand function. The supply chain involves one manufacturer and multiple suppliers and retailers, in which the latter two compete horizontally while keeping the Nash equilibrium, but all the three compete vertically while maintaining the Stackelberg equilibrium based on the assumption that, in the market, the manufacturer is stronger. Aiming at coordinating the company's ordering, pricing, and green product decisions, the followers' KKT (Karush–Kuhn–Tucker) conditions are replaced by the model's lower level (i.e. a one-level nonlinear programming model is obtained from a bi-level one). Parameters that are more effective on the demand, price, and profit are determined through a numerical example. According to obtained results, if the retailers' market competition is increased, their profit will increase, but an increase in the suppliers' market competition will reduce theirs; the results also show that, with increasing competition in the market, the overall supply chain profit will increase.

Keywords: Three-echelon supply chain; Competition; Pricing; Recycling; Green products; Game theory.

1. Introduction and Background

Since the technology is developing fast and competitions are quite close, the SC optimization is possible only through the corporates' close cooperation meaning that the market is experiencing an SC-to-SC instead of the common corporate-to-corporate competition [1].

Ever since the year 1990, such issues as the dual-channel SC coordination and price competition have been studied in various researches by different mechanisms including the RSC (Revenue Sharing Contract) [2, 3, 4], Q/PDC (Quantity/Price Discount Contract) [5, 6], ISC (Information

Sharing Contract) [7, 8] to mention some. Firms have long considered the pricing policy (in the SC/revenue management) as an effective means that could maximize their profit through manipulating the demand, regulating the production, and distributing the products/services [9].

Companies have concluded that if they improve their SC networks, much of the related environmental pollution pressure will be eliminated [10, 11]. Instead of the limited, traditional supply chains, companies should establish global ones because they are necessary for the development of the economic globalization. Global supply chains aim at ensuring not only the easy and fast product availability, but also minimizing the manufacturing, service, and performance costs. But, although the expansion of global SCs is economically beneficial, it consumes resources and pollutes the environment to both of which people are sensitive [12].

This is why hot topics are, nowadays, improving the resource utilization efficiency of global supply chains and lessening the manufacturing effects on the environment; the concept of the green supply chain, a novel idea aiming at minimizing environmental effects and maximizing resource efficiency (i.e. supplying materials and their processing, packaging, storage, transportation, and use) was thus born. Many countries and organizations have realized that resources will be utilized more efficiently and the environment will suffer less by the manufacturing if the green SC idea becomes true. They have adopted environmental protection and energy conservation strategies and try to update, improve, strengthen, and enforce the related laws and regulations [13].

Maroušek et al. [14, 15] tried to answer the question that “would it be possible to turn such bio-wastes as wheat husks, public greenery wastes, oats straw, and so on, into a biofuel that was potentially capable of being used in buildings, and if so, would it be economical?” Since the material they needed had to be inexpensive and environmentally clean (as regards the carbon emission), they analyzed the process parameters robustly to improve them at the market scale. Aiming at evaluating the impacts of novel solid biofuel production technologies, Hasˇkova [16] performed robust analyses to review their different aspects (environment, economy, health, social issues, etc.) to answer the customers´ questions when they decide to buy biofuels.

However, since the world population is growing fast and people act irresponsibly against the environment, pollution and natural resources scarcity are becoming serious problems. Therefore, it is time to get familiarized with the used products' recycling concept and apply it to our everyday life because it is necessary for a sustainable life. Accordingly, a very positive strategy is to buy products and recycle those thrown away [17, 18]. The following are some merits of recycling [19]:

- Future generations will have a sustainable environment.
- Not much raw materials need to be collected; therefore, pollution is reduced.
- Emission of greenhouse gases is reduced; hence, the global climate is preserved.
- Energy is saved.
- Since fresh raw materials are consumed less, natural resources are preserved.
- New jobs will be created in manufacturing/ recycling industries.
- Materials that are potentially useful are prevented from being wasted.

Such supply chain performance parameters as high customer satisfaction, low inventory cost, and suitable production capacity utilization can be improved through coordination [20] and many researches have focused on channel coordination for multi-echelon supply chains, but a few studies have considered coordination for pricing, recycling, and green products for over 2-echelon supply chains.

[21, 22, 23, and 24] have addressed joint pricing and order inventory for profit optimization in a SC where demand is affected by price, and have shown that individual decision making is not as much profitable as when decisions are made jointly. An economic order quantity model has been developed by Ghoreishi [25] has developed an economic order quantity model for products with selling prices influenced instantly by the inflation rate and the customer return.

Modak [17] has proposed cooperative/non-cooperative CLSC models involving one manufacturer and multiple retailers, under which duopolies retailers compete with one another under Stackelberg setting among manufacturers and retailers. A multi-echelon supply chain consisting of one manufacturer and multiple suppliers and retailers coordinates the company's different decisions such as inventory, advertising, ordering, and pricing Sadigh [26]. Based on a non-cooperative Nash game that considers both the pricing and inventory decisions, it proposes a new inventory model (for manufacturers as well as retailers) capable of determining the No. of orders for each product by considering the members' interrelations in a 3-echelon SC; to find the related game's equilibrium point, an iterative solution algorithm has been proposed.

Chung [27] has proposed a 3-echelon model for a pricing game and Jiang [28] has presented mathematical models for 3-contract mechanisms. Aust et al. [29] suggest the analyses of MEMs (multi-echelon models) with quality, advertising, and pricing decision variables as a research topic.

It is believed that the green supply chain management is increasingly finding its importance for companies that are highly aware of the global environmental effects [28, 30] and, at the same time, the number of the green SC-related academic studies are increasing too [31, 32 and 33]. CosKun et al. [34] have solved a hypothetical example problem of the real life to clearly emphasize the value and applicability of their proposed 3-consumer group (green, indifferent, and red) goal-programming model. Li et al. [35], propose a double-channel SC wherein the manufacturer produces green products for the environmental consciousness. Using the consistent pricing strategy in the Stackelberg game model, they discuss pricing and greening issues for the members of a supply chain in both centralized and decentralized cases and compare its results under one and two channel cases.

To meet different customers' needs and satisfy the market demand, a supply chain does not usually provide only one product and companies often try to offer a variety of products to maximize their profits and their shares in the market. Hence, this research has considered the multi-product approach in supply chain pricing and recycling decisions.

The raw material price and quantity are the suppliers' main decisions meaning that the wholesale price, product's green degree, and required raw materials are the decisions made by the manufacturer for his optimum net profit. It is assumed that those who are present in the market and compete are the retailers who sell the finished product they have bought at a wholesale price, to the final user at a retail price. Another assumption is that in the retail market, the rate of the demand increases with the price of the corresponding rival retailer, but decreases with the retail price.

As mentioned earlier, in the related literature review, many companies try to produce commodities which are not harmful for environment and be able to recycle them. Also, importance of products pricing effect to products demand and profit of supply chains' members and because the review of the literature shows no such effort has been made in a competitive market with complete compete hence this problem can be appealing.

Using a game theory modeling/ solution approach, effort has been made in this paper to address a gap found in the pricing/ recycling problem of green/ non-green products in a competitive 3-echelon SC for examine the competition among all three echelons’ participants to make decisions on what the price of their products should be. The findings showed that in competitive markets, retail prices are dependent on changes in demand, and necessarily increasing competition does not lead to lower prices while studies [26, 36] show that retail prices are decreasing with increasing competition.

The mathematical model in this paper has been presented as a non-cooperative, 3-echelon game wherein the players are the SC members. Retailers and suppliers compete in a Nash game horizontally. At the same time, they are involved playing in a separate game with the manufacturer. The system involves the leader (manufacturer) and the followers (suppliers and retailers); the former is more powerful and utters the last word. So the game is Stackelberg.

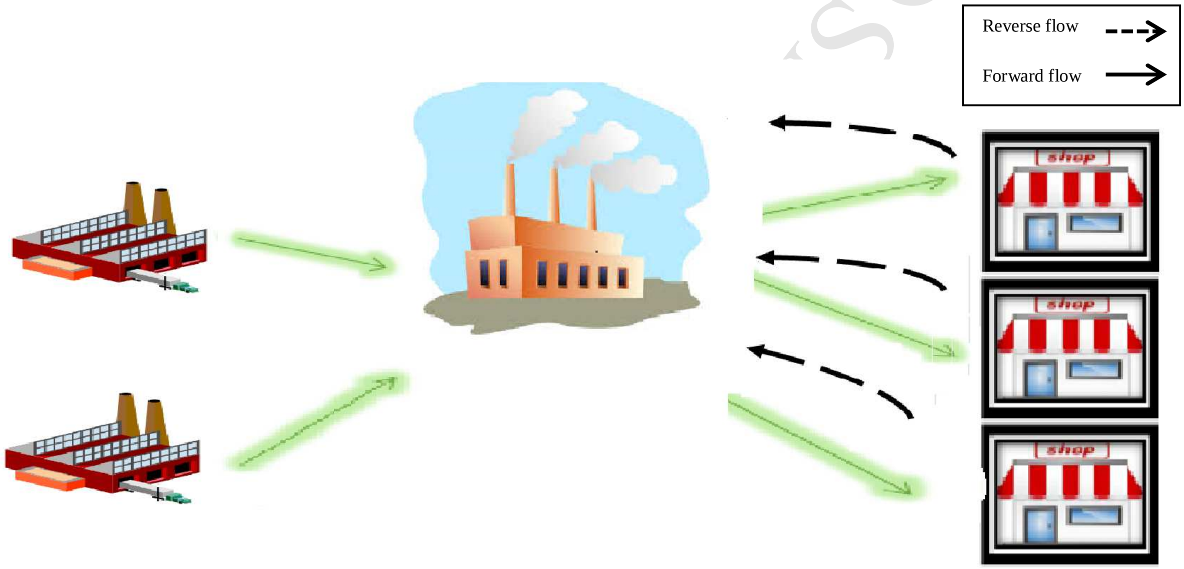


Fig 1: Scheme of 3-echelon supply chain

This paper has been so organized as present the mathematical model assumptions and notations in section 2, explain the computational and analytical model solution methods in section 3, provide some numerical examples to discussions of effects of competition in SC in section 4, in section 5 managerial insight is provided and conclude the results and future research suggestions in section 6.

2. Mathematical Model

In this section for modeling, the decision variables and parameters of the supply chain members are presented and a mathematical model for all of the members is presented.

2.1. Assumptions, signs, and symbols

This paper has based its proposed model on the following assumptions:

1) While demand (retailers') is linearly related to the retail price, rival retailer price, and the product greenness, the slope of its sales price is downward and that of its rival retailer price/ greenness is upward.
2) Green products do not influence common costs of the manufacturer who should invest extra money to produce green products through the existing production procedure; it is assumed that cost is a quadratic function of the product greenness.
3) All supply chain member parameters are deterministic and already known.
4) Since there is a complete competition between retailers and suppliers, for each product and every raw material, there must be at least two retailers and two suppliers to compete with each other.

Tables 1, 2, and 3 show the SC members' sets, parameters, and decision variables, respectively.

	Table 1. Sets of suppliers, manufacture, and retailers
W	Set of product number (w = 1, 2, …, n). The symbol "…" introduces a multi-member set.
Z	Set of retailers (z = 1, 2, …, Z)
O	Set of suppliers (n = 1, 2, …, O)
T	Set of raw materials for producing n products

	Table 2. parameters of suppliers, manufacture, and retailers
f_{wz}	A demand function scaling constant ($f_{wz} > 0$)
λ_{wz}	Product w's demand function price elasticity for retailer z
γ_{wz}	Product w's demand function price elasticity for the competitors of retailer z
C_w	Product w's unit production cost for the manufacturer
B_m	All products' maximum production budget
U_{tw}	Amount of raw material t needed for product w's unit production
Cs_{to}	Amount paid by supplier o for raw material t to be produced
m_{to}	Supplier o's maximum capacity for raw material t
η_{to}	Raw material t's price elasticity determined by supplier o
α_{to}	Raw material t's price elasticity determined by supplier o's competitors
K_z	Efficacy coefficient of greenness expansion for 1 unit green product
q_w	Per unit purchase cost of returned product w for the manufacturer
H_w	Per unit recycling cost of returned product w for the manufacturer
z	Products' fixed recycling cost
ω	Per unit greenness cost coefficient

2.2. Formulating the retailers' model

A (x_{wz}, ρ) (product demand at retailer z), related jointly and linearly to the retail price, rival retailer price, and product greenness, is as follows:

$$A_{wz} = f_{wz} - \lambda_{wz} x_{wz} + \sum_{z=1/z}^{Z} \gamma_{w\underline{z}} x_{w\underline{z}} + k_z \rho \quad (1)$$

	Table 3. Decision variables of supplier, manufacture, and retailers
x_{wz}	Product w's retailing price for retailer z
Φ_w	Product w's wholesale unit price
ρ	the green degree of the green products
y_t	Total raw material t needed for the production of all products
p_{to}	Raw material t's price charged to the manufacturer by supplier o
r_{to}	Total raw material t supplied by supplier o

where f_{wz} = a scaling parameter (always positive), λ_{wz} = price elasticity, and γ_{wz} = competitors' price elasticity.

Every retailer aims at maximizing his net profit through optimizing his decision variable i.e. the retail price. Therefore, the net profit of retailer z can be found as follows:

$$\underset{(x_{wz})}{\Pi_z} = \sum_{w=1}^{n} x_{wz} A_{wz} - \sum_{w=1}^{n} \varphi_w A_{wz} \tag{2}$$

Subjected.to.

$$x_{wz} \geq 0 \tag{3}$$

where Π_z is the retailer's net profit and the first expression shows the total profit from selling multiple products, and the second phrase is the purchasing cost from the manufacturer.

Non-negativity of the retail price is ensured by constraint (3).

2.3. Formulating the manufacturer's model

where z is the fixed rate of recycling products and ω is per unit greenness cost coefficient. It is assumed that the manufacturer's decisions include w (product wholesale price), ρ (product greenness), and y_t (required raw materials).

The manufacturer's net profit is as follows:

$$\prod_{(\varphi_w,\rho,y_t)}{}_M = \sum_{w=1}^{n}\left[\varphi_w \sum_{z=1}^{Z} A_{wz}\right] - \sum_{w=1}^{n}\left[C_w \sum_{z=1}^{Z} A_{wz}\right] \tag{4}$$

$$-\sum_{t=1}^{T}\sum_{o=1}^{O} p_{to} r_{to} - \sum_{w=1}^{n}\left[(q_w - h_w)\, b \sum_{z=1}^{Z} A_{wz}\right] - \frac{\omega\rho^2}{2}$$

Subjected.to.

$$\sum_{w=1}^{n}\sum_{z=1}^{Z} C_w A_{wz} \le B_m \tag{5}$$

$$y_t = u_{tw} \sum_{z=1}^{R} A_{wz} \quad \text{for t=1,2,...,T} \tag{6}$$

$$\varphi_z \ge 0,\ \rho \ge 0,\ y_t \ge 0 \tag{7}$$

where Π_M = net profit of the manufacturer, phrase 1 = profit of multiple products wholesaled to all retailers, phrase 2 = (product) production cost, and phrase 3 = raw materials purchasing cost. Constraint (5) limits the manufacturer (in spending the allocated production budget) to maximum B_m units for all products he produces and constraint (6) ensures the raw materials sufficiency to meet all retailers' demands (raw material is not to be short in the SC); And, constraint (7) shows the value range of the decision variables.

2.4. The suppliers' model formulation. Since pricing and amount of raw materials are the suppliers' decision variables, suppliers need to obtain their optimum strategies to maximize their net profits. They face the costs of supplying raw materials for the manufacture; thus, they obtain their revenues by selling them to him. The objective function for supplier *o* is thus:

$$\prod_{(p_{to},\, r_{to})} {}_{o} = \sum_{t=1}^{T} p_{to} r_{to} - \sum_{t=1}^{T} Cs_{to} r_{to} \tag{8}$$

Subjected.to.

$$r_{to} = y_t - \eta_{to} p_{to} + \sum_{t=1}^{T} \alpha_{to} p_{to} \tag{9}$$

$$\sum_{o=1}^{O} r_{to} = y_t \qquad \text{for t=1,2,...,T} \tag{10}$$

$$r_{to} \le m_{to} \qquad \text{for t=1,2,...,T} \tag{11}$$

$$p_{to} \ge 0,\; r_{to} \ge 0 \tag{12}$$

Constraint (9) ensures that demand depends on both the self- and other-offered prices of raw materials (i.e. suppliers compete with the manufacturer as well as among themselves). Constraint (10) ensures that suppliers supply the required raw materials. Since all suppliers can produce the t^{th} raw material, facing the w^{th} generalized Nash equilibrium point (GNEP) at the suppliers' level is common. Constraint (11) checks each supplier's production capacity for each raw material and constraint (12) ensures non-negativity of decision variables.

According to the framework of the Stackelberg game, one who decides on the wholesale price, required raw materials (y_t), and the product greenness is the manufacturer (leader) whereas the retailers and suppliers as the followers determine the retail price and price and amount of raw materials (produced by supplier) to maximize their profits.

Therefore, the model Stackelberg model will be as follows:

$$\prod_{(\varphi_w,\rho,y_t)} {}_M = \sum_{w=1}^{n}\left[\varphi_w \sum_{z=1}^{Z} A_{wz}\right] - \sum_{w=1}^{n}\left[C_w \sum_{z=1}^{Z} A_{wz}\right] \tag{13}$$

$$-\sum_{t=1}^{T}\sum_{o=1}^{O} p_{to} r_{to} - \sum_{w=1}^{n}\left[(q_w - h_w)\, b \sum_{z=1}^{Z} A_{wz}\right] - \frac{\omega\rho^2}{2}$$

$$Subjected.to.$$

$$\sum_{w=1}^{n}\sum_{z=1}^{Z} C_w A_{wz} \le B_m$$

$$y_t = u_{tw}\sum_{z=1}^{R} A_{wz} \qquad \text{for } t=1,2,\ldots,T$$

$$x_{wz} \in \arg uman \ \mathrm{Max} \prod_{(x_{wz})} {}_z = \sum_{w=1}^{n} x_{wz} A_{wz} - \sum_{w=1}^{n} \varphi_w A_{wz}$$

$$Subjected.to.$$

$$x_{wz} \ge 0$$

$$A_{wz} = f_{wz} - \lambda_{wz} x_{wz} + \sum_{z=1/z}^{Z} \gamma_{w\underline{z}} x_{w\underline{z}} + k_z \rho$$

$$(p_{to}, r_{to}) \in \arg uman \ \mathrm{Max} \prod_{(p_{to}, r_{to})} {}_o = \sum_{t=1}^{T} p_{to} r_{to} - \sum_{t=1}^{T} Cs_{to} r_{to}$$

$$Subjected.to.$$

$$r_{to} = y_t - \eta_{to} p_{to} + \sum_{o=1/o}^{O} \alpha_{t\underline{o}} p_{t\underline{o}}$$

$$\sum_{o=1}^{O} r_{to} = y_t \qquad \text{for } t=1,2,\ldots,T$$

$$r_{to} \le m_{to} \qquad \text{for } t=1,2,\ldots,T$$

3. Solution Method

By considering model formulation which has presented in the previous section, a 3-echelon SC with O suppliers, one manufacturer, and Z retailers (O+1+Z) has been presented, and the Stackelberg game concept to address the suppliers', manufacturer's, and retailers' strategies.

In this section, we will examine the manufacturer's Stackelberg model, in which the manufacturer has more power in the supply chain than retailers and suppliers, therefore manufacturer is leader and suppliers and retailers are called followers, so that at first he determines his own strategies and subsequently, retailers and suppliers determine their optimal amount. In other words, there is a bi-level problem. Also, the model presented in the Stackelberg game is a nonlinear and restricted model, on the other hand suppliers and retailers in the Nash game compete together horizontally simultaneously to gain more market share in order to gain more profit, therefore it's possible to solve it accurately by obtaining the optimal amount of players (suppliers and retailers) through the KKT conditions. The value of the objective function of the manufacturer is found by placing the KKT condition of the followers in the leader's problem and turning the bi-level problem into a single-level and it will show that this problem can be solved precisely and the equilibrium point of Stackelberg, in addition to being exist, is also unique.

In the previous section, it was presented nonlinear bi-level programming (NBP), in which the manufacture is leader, retailers and suppliers are followers.

The presented solution method is that the objective functions of the lower level players (retailers and suppliers) obtain their optimal values accurately using the values obtained from the higher level player (manufacture), next, to find the profit, they are given to the manufacturer.

To obtain the optimal retailer decisions, first-order condition of Equation (2) yields:

$$\frac{\partial \Pi R_z}{\partial p_{wz}} = 0 \quad \rightarrow x^*_{wz} = \frac{f_{wz} + \sum_{z=1/z}^{Z} \gamma_{w\underline{z}} x_{w\underline{z}} + k_z \rho + \lambda_{wz} \varphi_w}{2\lambda_{wz}} \tag{14}$$

Since the optimal best response does not need constraint (13) to be considered first, Lagrange equation and 1st order condition of the objective function of the supplier is as follows (β_t can be both +ive and –ive):

$$\begin{aligned} L_o(p_{to}) = & \sum_{t=1}^{T}\sum_{o=1}^{O} p_{to}\left(y_t - \eta_{to} p_{to} + \sum_{o=1/o}^{O} \alpha_{t\underline{o}} p_{t\underline{o}} \right) \\ & - \sum_{t=1}^{T}\sum_{o=1}^{O} Cs_{to}\left(y_t - \eta_{to} p_{to} + \sum_{o=1/o}^{O} \alpha_{t\underline{o}} p_{t\underline{o}} \right) - \beta_t\left(\sum_{o=1}^{O} r_{to} - y_t \right) \end{aligned} \tag{15}$$

$$\begin{aligned} \frac{\partial L_o}{\partial p_{to}} = 0 \quad \rightarrow \quad & \left(y_t - \eta_{to} p_{to} + \sum_{o=1/o}^{O} \alpha_{t\underline{o}} p_{t\underline{o}} \right) - \eta_{to}\left(p_{to} - Cs_{to} \right) \\ & - \beta_t\left(-\eta_{to} + (o-1)\alpha_{to} \right) = 0 \end{aligned}$$

To solve this model, the optimal strategies of the follower players, which are a function of the leader player' strategies, are placed in the leader's objective function, in such a way that the optimal values of the follower players' strategies, including retail prices, raw material prices form the constraints of the leader's (manufacturer) objective function. Therefore, the bi-level model will be subjected to the single-level model as follows:

$$\prod_{(\varphi_w,\rho,y_t)} {}_M = \sum_{w=1}^{n}\left[\varphi_w \sum_{z=1}^{Z} A_{wz}\right]-\sum_{w=1}^{n}\left[C_w \sum_{z=1}^{Z} A_{wz}\right] \tag{16}$$

$$-\sum_{t=1}^{T}\sum_{o=1}^{O} p_{to} r_{to} - \sum_{w=1}^{n}\left[(q_w - h_w)\, b \sum_{z=1}^{Z} A_{wz}\right] - \frac{\omega\rho^2}{2}$$

Subjected.to.

$$\sum_{w=1}^{n}\sum_{z=1}^{Z} C_w A_{wz} \le B_m$$

$$y_t = u_{tw}\sum_{z=1}^{Z} A_{wz} \qquad \text{for t=1,2,...,T}$$

$$x^*_{wz} = \frac{f_{wz} + \sum_{z=1/z}^{Z}\gamma_{wz} x_{wz} + k_z\rho + \lambda_{wz}\varphi_w}{2\lambda_{wz}}$$

$$\left(y_t - \eta_{to} p_{to} + \sum_{o=1/o}^{O}\alpha_{t\underline{o}} p_{t\underline{o}}\right) - \eta_{to}\left(p_{to} - Cs_{to}\right)$$
$$-\beta_t\left(-\eta_{to} + (o-1)\alpha_{to}\right) = 0$$

$$\sum_{o=1}^{O}\left[y_t - \eta_{to} p_{to} + \sum_{o=1/o}^{O}\alpha_{t\underline{o}} p_{t\underline{o}}\right] = y_t \qquad \text{for t=1,2,...,T}$$

Therefore, it is sufficient to show that the manufacture-objective function for the variables of follower players is concave function and manufacturer constrains make convex space that given in Appendix A.

Therefore, the manufacture's objective function in the Stackelberg model manufacturer will be as a function of the wholesale price and retail price and the product grade green variables.

$$\underset{(\varphi_w, y_t, \rho)}{Max}\,\Pi_M = \sum_{w=1}^{n}(\varphi_w - C_w)\sum_{z=1}^{Z}\Big(f_{wz} - \frac{f_{wz} + \sum_{z=z/1}^{Z}\gamma_{w\underline{z}} x_{w\underline{z}} + k_z\rho + \varphi_w\lambda_{wz}}{2} \tag{17}$$

$$+\sum_{z=z/1}^{Z}\gamma_{w\underline{z}} x_{w\underline{z}} + k_z\rho\Big) - \sum_{t=1}^{T}\sum_{o=1}^{O} p_{to} r_{to} - \sum_{w=1}^{n}(q_w - h_w) b \sum_{z=1}^{Z}\Big(f_{wz} - \frac{f_{wz} + \sum_{z=z/1}^{Z}\gamma_{w\underline{z}} x_{w\underline{z}} + k_z\rho + \varphi_w\lambda_{wz}}{2}$$

$$+\sum_{z=z/1}^{Z}\gamma_{w\underline{z}} x_{w\underline{z}} + k_z\rho\Big) - \frac{\omega\rho^2}{2}$$

$$\sum_{w=1}^{n} C_w \sum_{z=1}^{Z}\Big(f_{wz} - \frac{f_{wz} + \sum_{z=z/1}^{Z}\gamma_{w\underline{z}} x_{w\underline{z}} + k_z\rho + \varphi_w\lambda_{wz}}{2} + \sum_{z=z/1}^{Z}\gamma_{w\underline{z}} x_{w\underline{z}} + k_z\rho\Big) - B_m \le 0$$

$$u_{tw}\sum_{z=1}^{Z}\left(f_{wz}-\frac{f_{wz}+\sum_{\underline{z}=z/1}^{Z}\gamma_{w\underline{z}}x_{w\underline{z}}+k_z\rho+\varphi_w\lambda_{wz}}{2}+\sum_{\underline{z}=z/1}^{Z}\gamma_{w\underline{z}}x_{w\underline{z}}+k_z\rho\right)-y_t\leq 0 \qquad \text{for } t=1,2,...,T$$

$$\left(y_t-\eta_{to}p_{to}+\sum_{\underline{o}=o/1}^{O}\alpha_{t\underline{o}}p_{t\underline{o}}\right)-\eta_{to}\left(p_{to}-Cs_{to}\right)-\beta_t\left(-\eta_{to}+(o-1)\alpha_{to}\right)=0$$

$$\sum_{o=1}^{O}\left[y_t-\eta_{to}p_{to}+\sum_{\underline{o}=o/1}^{O}\alpha_{t\underline{o}}p_{t\underline{o}}\right]=y_t \qquad \text{for } t=1,2,...,T$$

Therefore, the bi-level programming model in which the manufacture plays leader roll becomes a single-level model.

The above model is a simple nonlinear single-level problem solved with optimization software GAMS24,1,2 and CONOPT solution tool and its general optimal answer is obtained at a logical time.

The general optimal answer of the above equation is the equilibrium point of the Stackelberg manufacture game, which in the next section, the results are analyzed.

4. Numerical study

This section describes how the proposed game model is applied and how effectively it solves the 3-echelon competitive SC. Important model features and managerial highlights have been illustrated through some numerical examples.

Example 1

Consider an SC wherein *s (supplier)* =1, 2, 3, and 4, manufacturer = 1, *z (retailer)* =1, 2, and 3, *t (material)* =1, 2, 3, 4, and 5, and *w (product)* =1, 2, 3 and 4. The SC members' input values are given in tables 4-6. The optimal values produced by the Stackelberg game for the decision variables of the manufacture are as follows: $\varphi_w{}^{*}$ = [39946.064; 45705.335; 47676.663; 38417.050] and $y_t{}^{*}$ = [48279.532; 60761.149; 82764.002; 28967.719; 22427.944]. In table 7, 8 the retailer's decision variables and the suppliers's decision variables are reported.

Table4. Parameters of retailers

retailer / sterategy	product	1	2	3
f_{wz}	1	60000	60000	70000
	2	60000	70000	60000
	3	70000	80000	87500
	4	71000	69000	69000
λ_{wz}	1	0.95	0.91	0.95
	2	0.93	0.89	0.95
	3	0.95	0.9	1
	4	1	1	0.995
γ_{wz}	1	0.001	0.006	0.004
	2	0.003	0.001	0.012
	3	0.001	0.002	0.013
	4	0.002	0.0013	0.001

Table5. Parameters of suppliers

supplier / strategy	Row material	1	2	3	4	supplier / strategy	Row material	1	2	3	4
α_{to}	1	0.01	0.04	0.05	0.07	η_{to}	1	20	20	20	20
	2	0.02	0.05	1	0.07		2	21	18	18	19
	3	0.03	0.04	0.01	0.05		3	11	19	19	19
	4	0.04	0.07	0.08	0.06		4	15	22	22	15
	5	0.02	0.05	0.07	1		5	18	12	12	26
Cs_{to}	1	0.5	1	0.7	0.4						
	2	0.6	0.25	0.35	0.5						
	3	0.35	0.5	0.45	0.5						
	4	0.3	0.2	0.25	0.4						
	5	0.025	0.55	0.25	0.1						

Table6. Parameters of manufacture

parameter / product	C_w	u_{1w}	u_{2w}	u_{3w}	u_{4w}	u_{5w}
1	2	1	1	0.5	0.6	0.2
2	3	0	0.6	2	0.3	0.4
3	4	0	1	0.3	0.3	0
4	5	0.5	0.4	1	0.4	0.4

Table7. variables of retailers

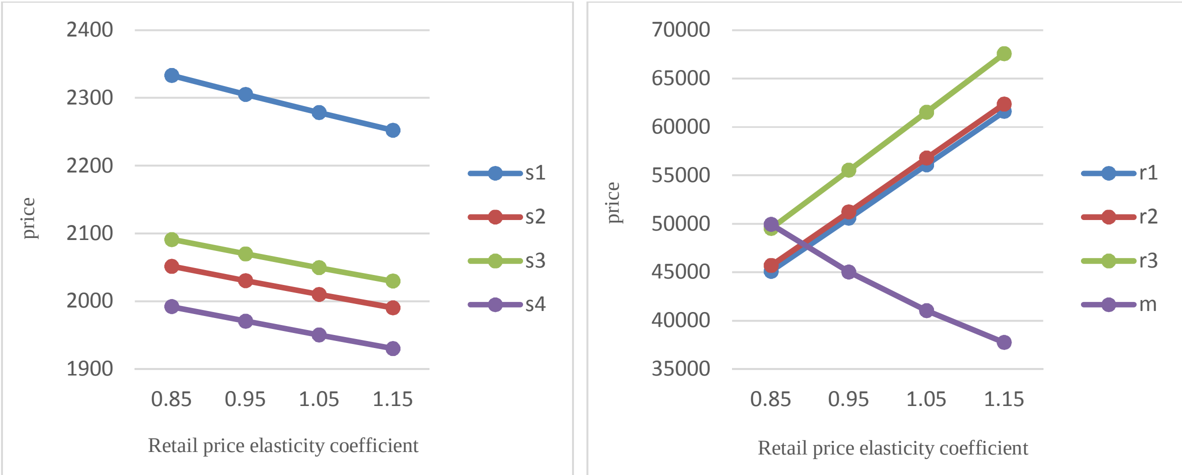
retailer / sterategy	product	1	2	3
x_{wz}	1	48866.317	47126.418	54437.347
	2	50039.833	52693.153	52225.032
	3	57360.370	58879.919	70838.169
	4	56987.638	57272.310	56584.630

Table8. variables of suppliers

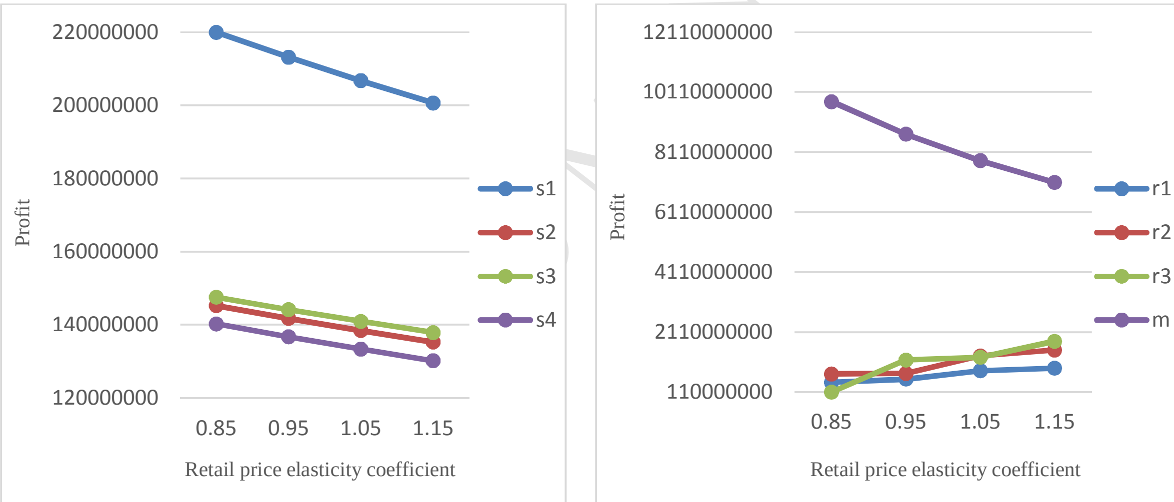
supplier sterategy	Row material	1	2	3	4	supplier sterategy	Row material	1	2	3	4
p_{to}	1	1868.797	1864.704	2265.161	1860.068	r_{to}	1	11221.63	11247.60	14525.60	11284.70
	2	2265.128	2501.549	2403.048	2408.835		2	13727.45	16187.50	15442.24	15403.96
	3	4984.341	3396.567	3295.611	3393.756		3	28274.76	18581.40	17306.86	18600.99
	4	1371.961	1061.057	1060.295	1369.495		4	8629.58	5846.33	5852.55	8639.26
	5	967.170	1277.054	1274.154	769.550		5	5248.88	7288.79	7298.25	2592.03

The profits earned by the retailers, manufacturer, and suppliers are $\Pi Z_1{}^*$ =791567800, $\Pi Z_2{}^*$ = 1135414000, $\Pi Z_3{}^*$ = 1358763000, $\Pi_M{}^*$ = 8242551000, $\Pi O_1{}^*$ = 209884800, and $\Pi O_2{}^*$ = 140061900, $\Pi O_3{}^*$ = 142525800, $\Pi O_4{}^*$ = 135024000, respectively.

A sensitivity analysis has been done to study λ_{wz}, γ_{wz}, and η_{to} (model main parameters); the mean prices and SC members' objective values are shown in Figs. 2, 3, 4, 5 and 6. To study the effects of the elasticity of the retail prices, the latter have been varied in the [$0.85\lambda_{wz}$; $1.15\lambda_{wz}$] interval and the effects on, respectively, the mean retail price, wholesale prices (of the two products) and the mean price of raw materials have been checked. As shown in Fig. 2, an increase in λ_{wz} increases the retail price but reduces the wholesale and raw materials prices, as regards the demand reduction is lower than the retail price increase (demand reduction is 12.13% and retail price increase is 25.67%), therefore retail profits grow, but the profits of manufacturer and suppliers decrease.



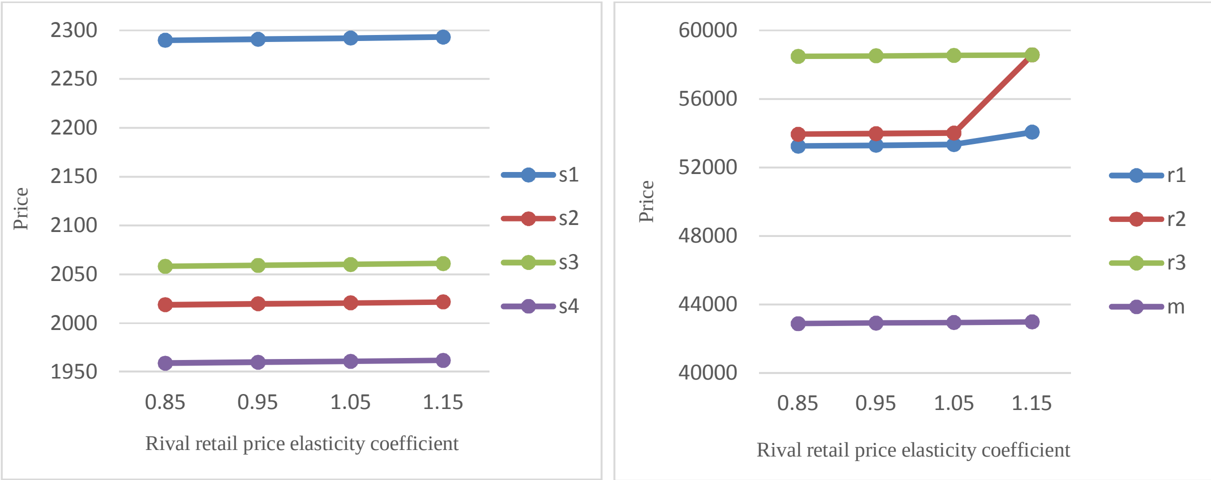
a) Effect of increasing λ on wholesale, retail and material raw prices



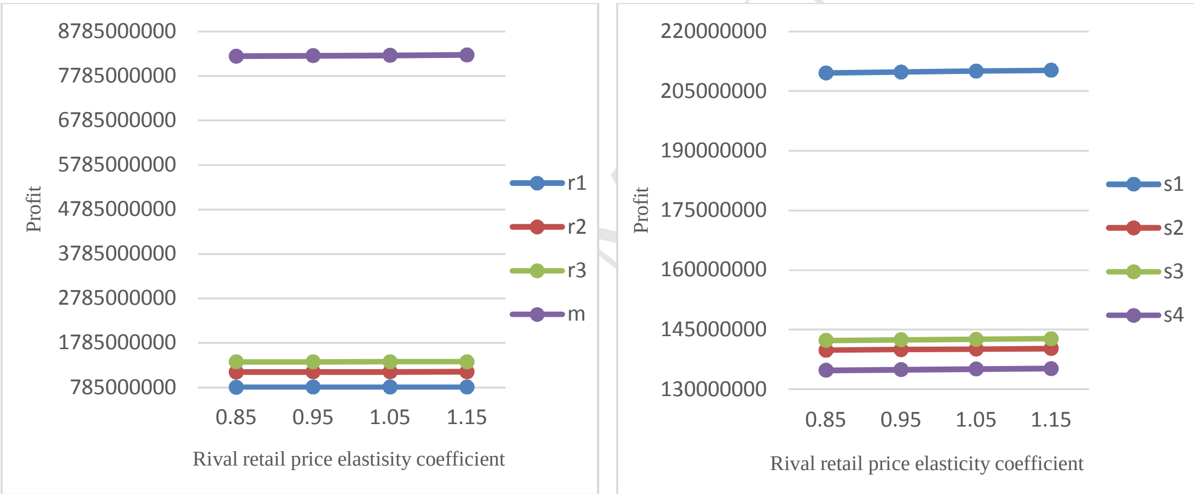
b) Effect of increasing λ on manufacture, retailers and suppliers profit

Fig 2. Sensitivity analysis on parameter λ

For γ_{wz} values in the $[0.85\gamma_{wz}; 1.15\gamma_{wz}]$ interval, effects of the elasticity of the rival prices and profits shown in Fig. 3; as shown, an increase in γ_{wz} increases the prices and, hence, the objective values for all the SC members.



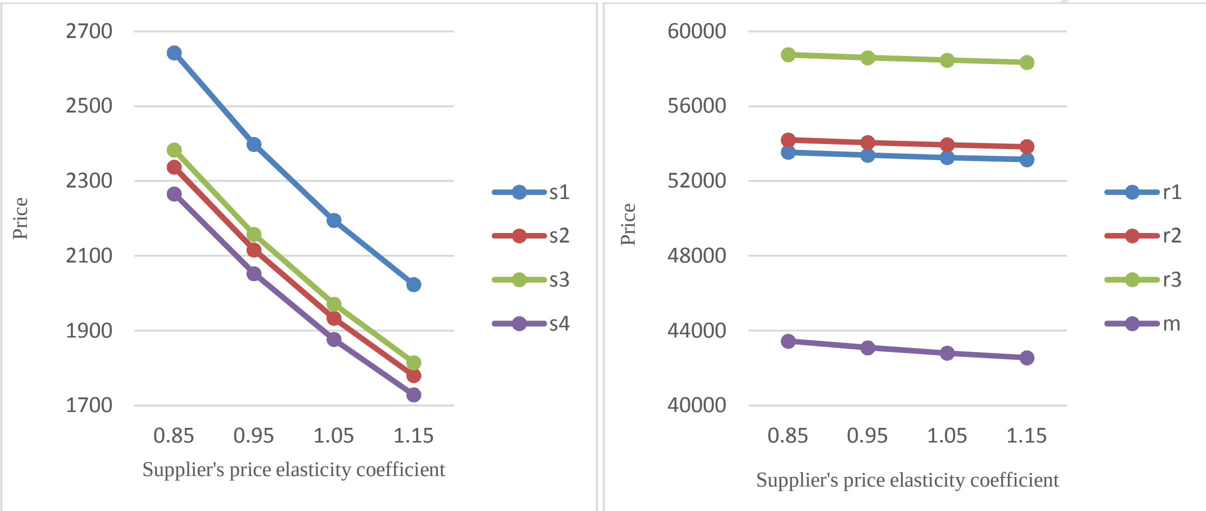
a) Effect of increasing γ on wholesale, retail and material raw prices



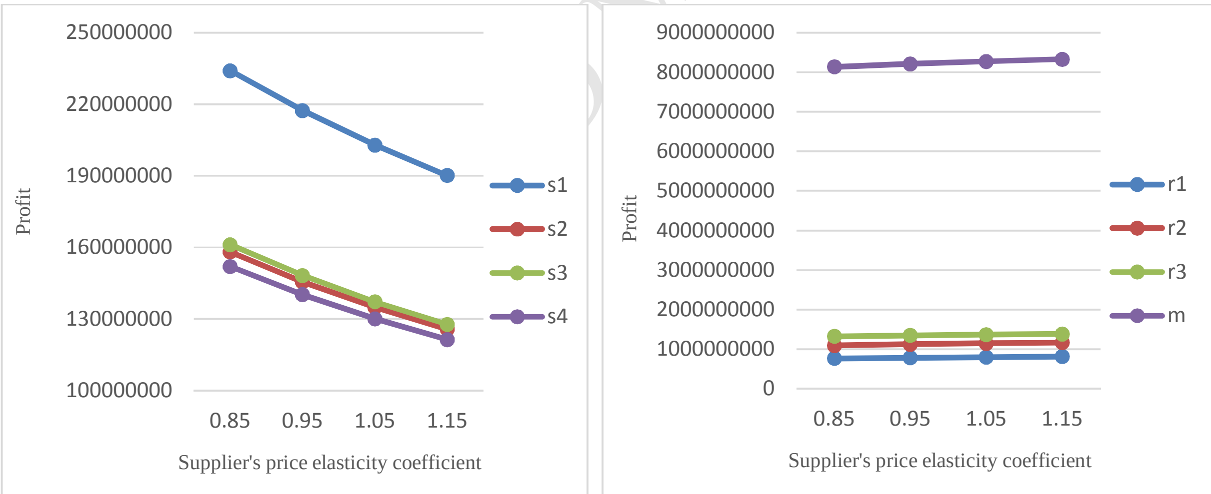
b) Effect of increasing γ on manufacture, retailers and suppliers profit

Fig 3. Sensitivity analysis on parameter γ

Fig. 4 shows the effects of the elasticities of the wholesale and raw materials prices for a change in the related parameter in the [0:85η_{to}; 1.15ηto] interval. According to Fig. 4a, an increase in the raw materials' price elasticity reduces the mean price of the suppliers, manufacturer, and retailers hence, increases the demand. According to the significant increase in demand in return for reducing retailers and manufacturer prices (demand increase is 0.63%, wholesale price reduction is 0.39% and retail price reduction is 0.28%), therefore the profit of retailers and manufacturer increases, but due to the fact that the price reduction of suppliers is higher than the increase in demand (raw material price reduction is 9.39%), the supplier's profit decreases as shown in figure 4b.



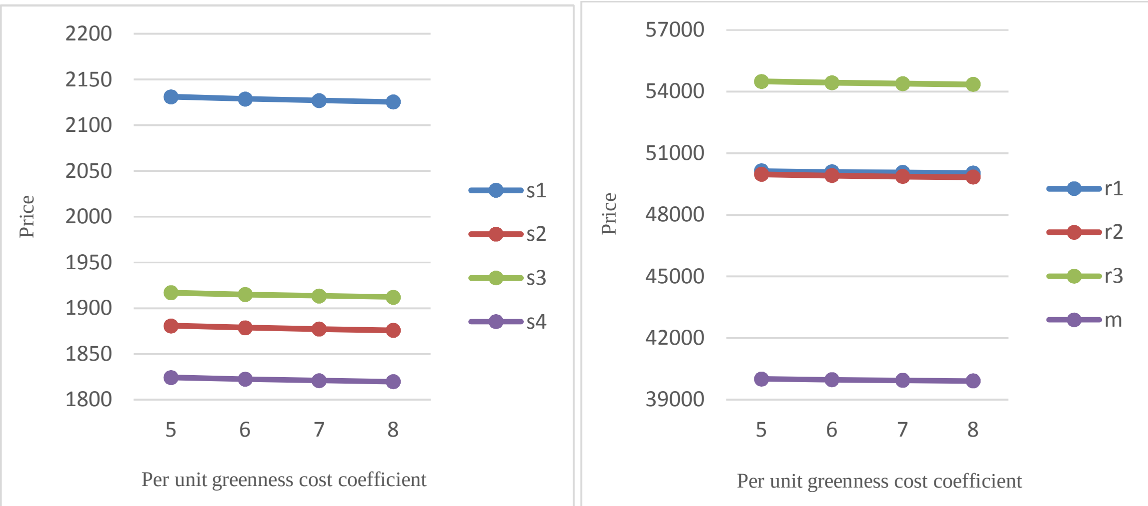
a) Effect of increasing η on wholesale, retail and material raw prices



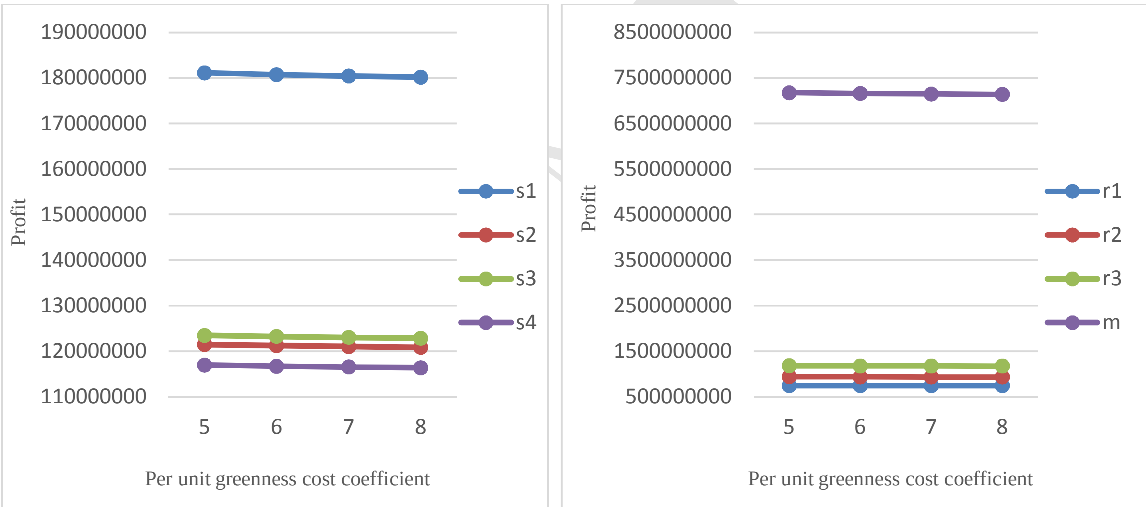
b) Effect of increasing η on manufacture, retailers and suppliers profit

Fig 4. Sensitivity analysis on parameter η

For ρ values in the [5; 8] interval, effects of the elasticity of the prices and profits shown in Fig. 5; as shown, an increase in ρ decreases the prices and demand, hence, the objective values for all the SC members.



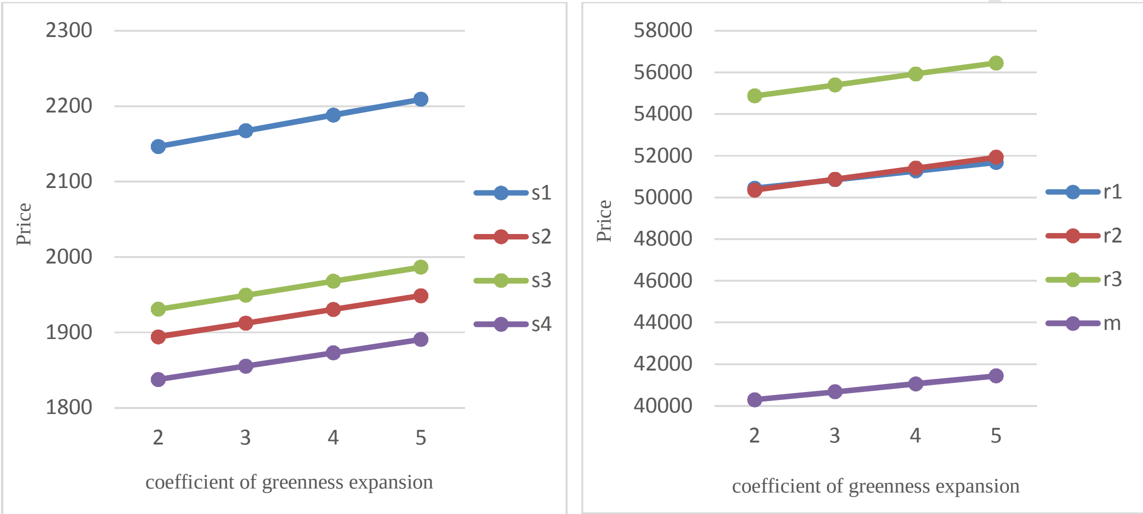
a) Effect of increasing ω on wholesale, retail and material raw prices



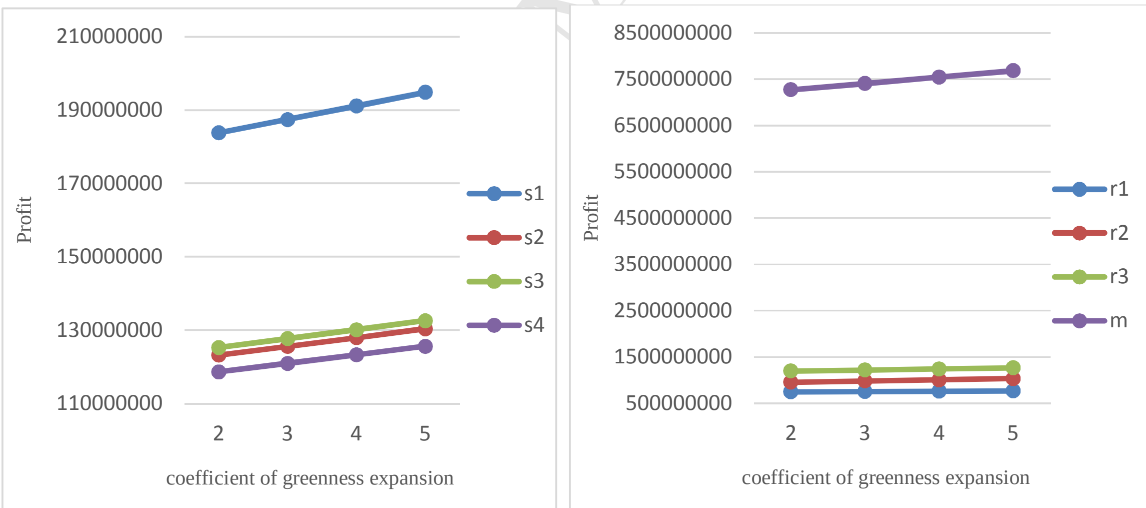
b) Effect of increasing ω on wholesale, retail and material raw profits

Fig 5. Sensitivity analysis on parameter ω

In Fig 6, we examine the changes of the efficacy coefficient of greenness expansion in the interval [2: 5], as we can see that increasing k_z leads to an increase in the price of all members of the supply chain. On the other hand, demand is also rising. So the product is greener the demand will increase.



a) Effect of increasing k_z on wholesale, retail and material raw prices



b) Effect of increasing k_z on wholesale, retail and material raw profits

Fig 6. Sensitivity analysis on parameter k_z

Example 2

More issues have been discussed here to explain the model performance in wider dimensions and converge to the equilibrium response in the Stackelberg manufacturer game. The dimension of the problem depends on the number of available products in the chain (w = 1,2, ... n), the number of retailers (z = 1,2, ..., Z), the number of raw materials needed to produce products (t = 1,2, ..., T) and the number of suppliers (o = 1,2, ..., O). Each of the issues in the Stackelberg game has been implemented and the average retail price, wholesale price and raw material price and average profit of retailers, manufacture, and suppliers have been reported.

Table 9. shows the average selling price of test problems at all levels of the chain.

Table9. Result test problem

Test Problem	Mean Objective Values			Mean Price		
	O	M	Z	O	M	Z
(4,4,2,2)	367079.45	99415080	174212500	154.39	4091.79	17462.4
(6,4,4,4)	3022262.30	285034100	255500725	340.03	4092.80	19468.50
(8,4,6,6)	11208710.25	736380200	328914133	533.57	5080.75	21017.62
(10,4,8,8)	35153717.5	158333500	504829050	87444	6509.77	25098.78

Table 9 shows the mean values of suppliers' raw materials price, manufacturer's all products' wholesale price, retailers' final products' retail price, and profits in the echelons of the suppliers, manufacturer, and retailers.

5. Managerial insights

According to Fig. 2 can infer that increasing self-price elasticity (λ_{wz}) declines the mean prices of suppliers, the manufacture and consequently reduces the total benefits of them but retail prices and profits increase with increasing self-price elasticity. In other words, due to the low flexibility of retail prices in highly competitive markets and demand reduction, players are forced to raise prices. This phenomenon is justified by the results in Fig. 3 On the contrary, if γ_{wz} is increased, all SC members average prices will increase which means more profit for them. Actually, high demand sensitivity to the rivals' price means more market excitement for increased demand and, hence, more profit for the SC.

Each supplier tries, in the supplier echelon, to acquire more demand in his competition with his rivals; the potential market demand for respective suppliers is formed by the amount of raw materials needed by the manufacture. According to Fig. 4.a, the greater is η_{to}, the more is the competition among suppliers, and this forces them to offer lower prices to the manufacture. Since the increase in demand is less than price reduction, the supplier's profit has been reduced in Fig. 4.b. Hence, both the manufacture and retailers offer lower prices leading to more demand through the SC. And since the increase in demand is more than the wholesale and retail prices, the manufacture and retailers' profits increase. Fig. 5 shows that an increase in cost per unit greenness will reduce the SC members' profits and prices as well as demand. Also it represents an increase in the cost of investment in the production of green products which does not encourage the manufacturer to produce green products. The analysis of Fig. 6 shows that the more effective the coefficient of greenness expansion in the competitive markets, the more willing customers will be in green products, so demand will increase and the members of the supply chain will earn more. In real world the "new achievement" mentioned above can be applied to LED lights (with an energy utilization of 30% compared to tube lights and considerably less heat generation), intelligent irrigation (with management and watering systems specific to the site), and so on. A well-known environmental sustainability manufacturer as Allergan and Unilever can use the proposed model to enhance its competitive power and raise its profit.

In the large size problems, the proposed model can be hardly solved which is the most common limitation in the mathematical models. Therefore, we propose metaheuristic algorithms to solve the model in these problems.

6. Conclusions

This paper has investigated the coordination of the decisions of pricing, recycling, and green products through a three-echelon competitive SC with one manufacturer, more than one supplier, and many retailers. All SC participants make pricing decisions, green products are produced by the manufacturer, and unprocessed products are sold, for recycling, to the manufacturer by the retailers; all these coordination decisions have been formulated in the form of a Stackelberg game.

This paper has studied the extent the retailers' market can be competitive and has shown that, contrary to the earlier researches [26, 36], the price and profit margins of the retailers will not reduce because they sell their products at higher prices. A point worth noting is that an increase in cost per unit greenness will reduce the price and profit of all the chain members because the demand is also reduced. Therefore, in this situation, the manufacturer is not willing to invest more money to improve the green products. Furthermore, we explore how the coefficient of greenness expansion influences the green supply chain. By increasing the coefficient of greenness expansion, demand will increase, so retailers are willing to buy the green products from the manufacturer, and the manufacturer will also show more willingness to produce the green products to increase itself profit. The proposed model is beneficial to manufacturers active in competitive markets because it enables them to not only lessen the amount of the produced waste/ waste water and emission of different harmful gases, but also win the competition and improve the whole SC profitability. It is also beneficial to the government and policymakers because manufacturers welcome more investments and customers are encouraged to purchase such products.

It is suggested, for future studies, to develop the model for larger problem sizes to consider more competing manufactures. In this paper, it is assumed that all parameters of the model are deterministic, the probable demand in addition to price dependence and the degree of greenness of the product can be a very good ground for future research in the competitive supply chain. Other interesting areas suggested for future researches can be “multi-period environments”, “recycling-based dynamic pricing”, and “green products’ decisions”.

Appendix A

Proving that the manufacture objective function is fully pseudo concave: A buyer's objective function being fully pseudo concave has been shown by Sadigh [37].

Lemma 1: The objective function of the Stackelberg manufacture is fully pseudo concave concerning the wholesale price variables.

If S is assumed to be a nonempty open set in En, differentiation of (f: S → En) is possible on S, and inequality $\nabla f(x_1)(x_2 - x_1) < 0$ applies to x_1 and x_2 for $f(x_2) \leq f(x_1)$, function f will be fully pseudo convex. If f is pseudo convex then −f is pseudo concave [37].

Suppose the inequality ∏b (P2, M) ≤ ∏b (P1, M), is equivalent to:

$$-A_2(\varphi_2 - C - (q-h)b) \leq -A_1(\varphi_1 - C - (q-h)b) \quad (18)$$

After simlifying the above equation changes as follows:

$$\varphi_2\left(f + \gamma x + k\rho - \lambda\varphi_2 - \lambda C - \lambda(q-h)b\right) \leq \varphi_1\left(f + \gamma x + k\rho - \lambda\varphi_1 - \lambda C - \lambda(q-h)b\right) \quad (19)$$

Now, the first-order condition of the manufacture's objective function respect to φ_1 is as follows:

$$\frac{\partial \Pi_M}{\partial \varphi_1} = \frac{1}{2}(f + \lambda(x - 2\varphi_1 + C + (q-h)b) + k\rho) \quad (20)$$

According to equation (20), derivation of the manufacture's objective function is in the following two situations:

$$\varphi_1 \geq \frac{f + \lambda(x + C + (q-h)b) + k\rho}{2\lambda} \rightarrow \frac{\partial \Pi_M}{\partial \varphi_1} \prec 0 \quad (21)$$

$$\varphi_1 \leq \frac{f + \lambda(x + C + (q-h)b) + k\rho}{2\lambda} \rightarrow \frac{\partial \Pi_M}{\partial \varphi_1} \succ 0 \quad (22)$$

First, it is assumed that the value of φ_1 in equation (21) is true, So for establishing relation (19) it is necessary to have the value φ_2 in the following equation.

$$\frac{f + \lambda(x + C + (q-h)b) + k\rho}{2\lambda} \leq \varphi_1 \leq \varphi_2 \quad (23)$$

So the following relation will be established.

$$\varphi_1 \le \varphi_2 \rightarrow \frac{\partial \Pi_M}{\partial \varphi_1}(\varphi_2 - \varphi_1) \prec 0 \quad (24)$$

Now it is assumed that the value φ_1 in (22) is true, also, According to Lemma assumption, equation (22) which is an increasing function, The value of φ_2 can never be greater than the value of the variable φ_1. So the following relation can be deduced.

$$\varphi_1 \ge \varphi_2 \rightarrow \frac{\partial \Pi_M}{\partial \varphi_1}(\varphi_2 - \varphi_1) \prec 0 \quad (25)$$

In two cases of φ_1, it was shown that the relation $\frac{\partial \Pi_M}{\partial \varphi_1}(\varphi_2 - \varphi_1)$ exists, so that the pseudo-concave proof of the manufacture's objective function in the Stackelberg model is complete with respect to the wholesale price variable.

Lemma 2: The objective function of the Stackelberg manufacture is fully pseudo concave concerning the product greenness variable.

Proof: Similarly, it is shown that the derivation of the manufacture's objective function with respect to the product grade green variables is in the following two situations:

$$\rho_1 \ge \frac{kC + k(\mathrm{q} - \mathrm{h})b - k\varphi}{2\omega} \rightarrow \frac{\partial \Pi_M}{\partial \rho_1} \succ 0 \quad (26)$$

$$\rho_1 \le \frac{kC + k(\mathrm{q} - \mathrm{h})b - k\varphi}{2\omega} \rightarrow \frac{\partial \Pi_M}{\partial \rho_1} \prec 0 \quad (27)$$

As a result is similarly, in two cases of ρ_1, it was shown that the relation $\frac{\partial \Pi_M}{\partial \rho_1}(\rho_2 - \rho_1)$ exists, so that the pseudo-concave proof of the manufacture's objective function in the Stackelberg model is complete with respect to the product grade green variable.

Lemma 3: The Stackelberg manufacture's solution space set constitutes a convex set.

Proof: In order to show the convexity solution space, first the smaller equal inequality constraints are investigated.

$$\sum_{w=1}^{n}\sum_{z=1}^{Z} C_w A_{wz} \leq B_m \tag{28}$$

$$u_{tw}(\sum_{z=1}^{Z} A_{wz}) - y_t \leq 0 \qquad \forall t=1,2,...,T \tag{29}$$

Given that the above constraints are smaller equal equation, the demand equation must be convex, since the demand equation is linear, the space is convex.

Also, since all of the equal constraints are linear, and if the equal constraints are linear, the solution space will be convex. Thus, the space of the solution of the Stackelberg model constitutes a convex set. As a result, according to the lamma1,2 and 3 the existence and uniqueness of the Stackelberg equilibrium point is proved.

References

[1] Fang, Y., & Shou, B. (2015). Managing supply uncertainty under supply chain Cournot competition. *European Journal of Operational Research*, 243(1), 156-176.

[2] Xiao, J., Dan, B., & Zhang, X. M. (2009). Study on cooperation strategy between electronic channels and retailers in dual-channel supply chain. *Journal of Systems Engineering*, 24(6), 673-679.

[3] Zhengping, D., & Yezheng, L. (2013). Revenue sharing contract in dual channel supply chain in case of free riding [J]. *Journal of Systems Engineering*, 3, 012.

[4] Hong, Z., & Guo, X. (2019). Green product supply chain contracts considering environmental responsibilities. *Omega*, 83, 155-166.

[5] Shin, H., & Benton, W. C. (2004). Quantity Discount-Based Inventory Coordination: Effectiveness and Critical Environmental Factors. *Production and Operations Management*, 13(1), 63-76.

[6] Cai, G. G. (2010). Channel selection and coordination in dual-channel supply chains. *Journal of Retailing*, 86(1), 22-36.

[7] Yue, X., & Liu, J. (2006). Demand forecast sharing in a dual-channel supply chain. *European Journal of Operational Research*, 174(1), 646-667.

[8] Cao, E., Ma, Y., Wan, C., & Lai, M. (2013). Contracting with asymmetric cost information in a dual-channel supply chain. *Operations Research Letters*, 41(4), 410-414.

[9] Soon, W. (2011). A review of multi-product pricing models. *Applied mathematics and computation*, 217(21), 8149-8165.

[10] Saberi, S., Cruz, J. M., Sarkis, J., & Nagurney, A. (2018). A competitive multiperiod supply chain network model with freight carriers and green technology investment option. *European Journal of Operational Research*, 266(3), 934-949.

[11] Zhao, R., Liu, Y., Zhang, N., & Huang, T. (2017). An optimization model for green supply chain management by using a big data analytic approach. *Journal of Cleaner Production*, 142(2), 1085-1097.

[12] Genovese, A., Acquaye, A. A., Figueroa, A., & Koh, S. L. (2017). Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications. *Omega*, 66, 344-357.

[13] Song, H., & Gao, X. (2018). Green supply chain game model and analysis under revenue-sharing contract. *Journal of Cleaner Production*, 170, 183-192.

[14] Maroušek, J. (2014). Biotechnological partition of the grass silage to streamline its complex energy utilization. International journal of green enery, 11(9), 962-968.

[15] Maroušek, J. (2015). Managing environmental innovation: Case study on biorefnery concept. Revista Técnica de la Facultad de Ingeniería Universidad del Zulia, 38(3).

[16] Hašková, S. (2017). Holistic assessment and ethical disputation on a new trend in solid biofuels. Science and engineering ethics, 23(2), 509-519.

[17] Modak, N. M., Panda, S., & Sana, S. S. (2016). Two-echelon supply chain coordination among manufacturer and duopolies retailers with recycling facility. *The International Journal of Advanced Manufacturing Technology*, 87(5-8), 1531-1546.

[18] Govindan, K., & Soleimani, H. (2017). A review of reverse logistics and closed-loop supply chains: a Journal of Cleaner Production focus. *Journal of Cleaner Production*, 142, 371-384.

[19] Jafari, H., Hejazi, S. R., & Rasti-Barzoki, M. (2017). Sustainable development by waste recycling under a three-echelon supply chain: A game-theoretic approach. *Journal of cleaner production*, 142, 2252-2261.

[20] Ramdas, K., & Spekman, R. E. (2000). Chain or shackles: understanding what drives supply-chain performance. *Interfaces*, 30(4), 3-21.

[21] Yugang, Y., Liang, L., & Huang, G. Q. (2006). Leader–follower game in vendor-managed inventory system with limited production capacity considering wholesale and retail prices. *International Journal of Logistics: Research and Applications*, 9(4), 335-350.

[22] SeyedEsfahani, M. M., Biazaran, M., & Gharakhani, M. (2011). A game theoretic approach to coordinate pricing and vertical co-op advertising in manufacturer–retailer supply chains. *European Journal of Operational Research*, 211(2), 263-273.

[23] Esmaeili, M., & Zeephongsekul, P. (2010). Seller–buyer models of supply chain management with an asymmetric information structure. *International Journal of Production Economics*, 123(1), 146-154.

[24] Shi, J., & Xiao, T. (2015). Service investment and consumer returns policy in a vendor-managed inventory supply chain. *Journal of Industrial & Management Optimization*, 11(2), 439-459.

[25] Ghoreishi, M., Mirzazadeh, A., Weber, G. W., & Nakhai-Kamalabadi, I. (2015). Joint pricing and replenishment decisions for non-instantaneous deteriorating items with partial backlogging, inflation-and selling price-dependent demand and customer returns. *MANAGEMENT*, 11(3), 933-949.

[26] Sadigh, A. N., Chaharsooghi, S. K., & Sheikhmohammady, M. (2016). A game theoretic approach to coordination of pricing, advertising, and inventory decisions in a competitive supply chain. *Journal of Industrial and Management Optimization*, 12(1), 337-355.

[27] Chung, W., Talluri, S., & Narasimhan, R. (2011). Price markdown scheme in a multi-echelon supply chain in a high-tech industry. *European Journal of Operational Research*, 215(3), 581-589.

[28] Jiang, L., Wang, Y., Yan, X., & Dai, W. (2014). Coordinating a three-stage supply chain with competing manufacturers. *Central European Journal of Operations Research*, 22(1), 53-72.

[29] Aust, G. (2015). Cooperative advertising models in supply chain management: A review. In Vertical Cooperative Advertising in Supply Chain Management. *Springer*, Cham.

[30] Srivastava, S. K. (2007). Green supply-chain management: a state-of-the-art literature review. *International journal of management reviews*, 9(1), 53-80.

[31] Sarkis, J. (2003). A strategic decision framework for green supply chain management. *Journal of cleaner production*, 11(4), 397-409.

[32] Govindan, K., Rajendran, S., Sarkis, J., & Murugesan, P. (2015). Multi criteria decision making approaches for green supplier evaluation and selection: a literature review. *Journal of Cleaner Production*, 98, 66-83.

[33] Seuring, S. (2013). A review of modeling approaches for sustainable supply chain management. *Decision support systems*, *54*(4), 1513-1520.

[34] Coskun, S., Ozgur, L., Polat, O., & Gungor, A. (2016). A model proposal for green supply chain network design based on consumer segmentation. *Journal of Cleaner Production*, 110, 149-157.

[35] Li, B., Zhu, M., Jiang, Y., & Li, Z. (2016). Pricing policies of a competitive dual-channel green supply chain. *Journal of Cleaner Production*, 112, 2029-2042.

[36] Sadigh, A. N., Chaharsooghi, S. K., & Sheikhmohammady, M. (2016). Game-theoretic analysis of coordinating pricing and marketing decisions in a multi-product multi-echelon supply chain. *Scientia Iranica. Transaction E*, Industrial Engineering, 23(3), 1459.

[37] Sadigh, A. N., Karimi, B., & Farahani, R. Z. (2011). A game theoretic approach for two echelon supply chains with continuous depletion. *International Journal of Management Science and Engineering Management*, 6(6), 408-412.

Highlights

- This research considers a competitive green three-echelon supply chain that the manufacturer determines additional investment in producing green products.
- Both horizontal and vertical competitions among all the multi-product supply chain members are addressed.
- Optimal pricing is determined in all three-echelon supply chain.
- Both Stackelberg and Nash games' approaches are considered in the whole supply chain.
- This study have shown that increasing of coefficient of greenness expansion not will the demand increase, but also increase the profit of all members of the supply chain.