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A game theoretical approach for a green supply chain: A case study in hydraulic-pneumatic industry

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A B S T R A C T

As customers' orientation towards environmental products increases, manufacturers and other members of the supply chain are looking for ways to conduct their operations in an environmentally and cost-effective manner. To find a solution that compensates these requests, a game theoretical approach is developed for a two-stage green supply chain consisting of a supplier and a producer. A Stackelberg game model based on asymmetric information structure is developed to find the optimal lot sizes and raw material sales price for raw material supplier, and the product sales price and the environmental cost for the producer. The developed approach is illustrated on a real-world case study that deals with production and raw material procurement processes of a plastic plug and compared to a scenario in which no environmental expenditures exist. The effect of changes in the model has been observed by tuning some significant parameters with the experimental design approach.

1. Introduction

Thinking companies are independent of each other has become impossible since there is a holistic approach in supply chains. These companies are connected to each other in all respects. Therefore their success does not only dependent on themselves, but is influenced by all the companies in the chain. The game theory methodology intends to maximize the total benefit of the individuals. Inevitably, the application of game theory in the supply chain is prosperous. Supply chain processes inherently involve upstream and downstream activities. The term upstream represents the raw material flow into a producing company in a chain, while the downstream refers to the final activities used to create finished goods and distribution and sale of the goods (Waters, 2003). Supply chain is suitable for modeling with the Stackelberg game due to this structure in different echelons.

Green supply chain management, which is a more current approach, has emerged with increasing awareness of environmental damage. Governments and businesses set environmental goals to minimize these negative impacts and entail compliance with these rules. Thus, a supply chain management concept is formed with green concerns.

In this study, we contemplate a game theoretic model for a two-stage green supply chain that contains a producer and a raw material supplier. In our model, the producer procures the raw material from one supplier, produces and sells the specific product to the customers in demanded quantity. It is known that the demand for environmental products has increased with the awareness of environmental responsibility developed in recent years. Companies incur some costs in order to produce environmental products of the desired quality, such as recycling costs and additional material costs. Therefore, in this model, we assume that demand is positively affected by environmental costs.

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Sharing information which is a method of cooperation between companies in the supply chain is essential since it provides competitive advantage. Firms, in general, make more profit when they collaborate as the supply chain risks arising from uncertainty are reduced. (Zhang & Liu 2013). However, in most of the supply chains in which the competition is intense, most companies do not agree to share information. Models with asymmetric information are utilized when the information sharing is not considered. Unfortunately, models with asymmetric information structure are scarce due to its complexity (Esmaeili and Zeephongsekul, 2010; McCluskey, 2000; Zhu and Weyant, 2003; Amann and Leininger, 1996). However, an asymmetrical model is essential to make the models more suitable for real life. In this study, the raw material supplier naturally knows his own costs such as setup and purchasing costs and the demand function, since the amount requested is directly proportional to the demand. However, it is not possible for the producer to know the costs of the raw material supplier. This forms an asymmetrical information structure, that is, the situation where the parties do not have equal information.

In the literature, vendor-buyer models aiming to find the optimum marketing cost are common. There are few studies based on the symmetric information structure that is modelled with the Stackelberg game in supply chain. (Barari et al., 2012; Esmaeili et al. 2016). However, as far as known, a Stackelberg game model that optimizes lot size, prices and environmental cost with an asymmetric information structure in the green supply chain has not been examined yet. A case study in the Hydraulic-Pneumatic industry is presented to illustrate the proposed model. Two different scenarios are discussed in the study: By producing the product in an environmentally friendly manner and positioning it in the market, and with traditional production. Based on this, the environmental cost and product price which ensure maximum profit for both the producer and the supplier in the supply chain are determined. Then, we develop a full factorial experimental design approach to observe the changes on the actual results by alterations of some significant parameters. 27 scenarios that examine the three factors (the setup and the production costs of the supplier and the greening elasticity of demand coefficient) that cause asymmetric information for both parties are discussed at three levels. The effects and interactions of these three factors on lot size, raw material sales price, the product price, the environmental expenditures and profit functions are analyzed.

The paper is established as follows: In Section 2, an expedient literature review is provided. The definition of the problem including the Stackelberg game model based on asymmetric information is presented in Section 3. The application of the model to a real-life problem and the scenario analysis with the experimental design methodology are given in Section 4. The final section concludes the study and provides insights and future directions.

2. Literature Review

There is a growing interest and a vast literature on game theoretical applications in Green Supply Chain Management although it is a relatively new field. Dockner and Van Long (1993) use cooperative and non-cooperative game theory approaches in the chain that consists of the government and the producer, to minimize the pollution level. Majumder and Groenevelt (2001) model the competition between a manufacturer and a remanufacturer by creating the Nash equilibrium. Brunner and Starkl (2004) develop a cooperative game theory approach to procure sustainable water management. Sturm and Weimann (2006) examine the consumption of common resources with game theoretic approaches. Zhu and Dou (2007) apply evolutionary game theory to a supply chain with environmental objectives that consists of government and businesses. Bernard et al. (2008) include dynamic game theory and use the Cournot-Nash equilibrium in their study on carbon emission trade which emerges with the Kyoto protocol. Zhao et al. (2012) develop a game theory approach in order to diminish carbon emission in an environmentally friendly supply chain in which government and producers are involved. For detailed review on game theoretic techniques in green supply chain management please refer to Agi et al. (2021).

Over the last few years, there has been an elevation in Stackelberg game applications in green supply chains. Zhang and Liu (2013) implement the Stackelberg game in a three-tier green supply chain that consists of a supplier, a producer and a retailer. Tian et al. (2014) build an evolutionary game theory approach and a simulation methodology having regard to the diffusion rate of the supply chain of automobile manufacturers and the payoffs of the manufacturers. Du et al. (2015) present a Stackelberg game approach between the government and the company that must comply with the emission limit set by the government in a supply chain in which emissions trading is possible. Cao et al. (2016) organize a Stackelberg game on the carbon emission amount in a two-tier supply chain consisting of a producer and a retailer. In order to lessen carbon dioxide emissions and maximize the profits, Huang et al. (2016) implement the Stackelberg game model in a supply chain which contains a producer with a large number of suppliers and retailers and utilize the genetic algorithm to achieve a solution. Hong et al. (2017) design a Stackelberg game model where the local government is the leader, and the companies are the followers in a multi-echelon supply chain. Wang et al. (2017) propose an approach which maximizes the overall profit and environmental goodness by the Stackelberg method in the 2-level and 3-level supply chain under the carbon emission constraint set by the government. Moradinasab et al. (2018) develop a game theoretical methodology for sustainable petroleum supply chain by the Stackelberg and Nash equilibria.

In supply chain literature, vendor-buyer models that integrate inventory decisions with pricing, or advertising decisions are common. For instance, He et al. (2020), develop a two-level supply chain model entailing a vendor and a retailer, and propose a Stackelberg game model that enables them to make inventory and pricing decisions. Yadav et al. (2021) propose a vendor-buyer Stackelberg game model with imperfect quality items under symmetric information structure. The reader interested in a detailed review on this subject may refer to Aust and Buscher (2014). Although a large amount of research has been conducted in the last few years on vendor-buyer models with Stackelberg game theoretic approach, applications under asymmetric information are not abundant. For instance, Yu et al. (2009a) discuss a vendor managed inventory (VMI) system in an asymmetric environment to maximize profits by regulating optimal advertising, pricing, and inventory policies. Esmaeili and Zeephongsekul (2010) model a supply chain which consists of a seller and buyer to obtain optimal lot size, price and advertising cost with asymmetric information. Wei et al. (2015) develop a Stackelberg game model for pricing and collecting resolutions under complete and incomplete information structure. However, many of these studies do not take environmental concerns into account. The studies of Barari et al. (2012) and Bao and Zhang (2018) are among the rare studies that take into account the environmental effects in the vendor-buyer supply chain model established with the Stackelberg approach. Barari et al. (2012) deal with optimal pricing, inventory, advertising and green advertising decisions while Bao and Zhang (2018) address the production-inventory-sourcing and supplier selection problems.

In Table 1, a summary of relevant literature in terms of problem characteristics (such as properties of players and information structures), solution methodologies and whether or not to address environmental concerns, is given.

Table 1
An overview of Stackelberg game models that optimize the sales price, lot size, marketing or greening expenditures

Paper	# of Players	Properties of Players	Methodology	Information Structure	Analysis method	Environmental Concerns
Viswanathan and Wang (2003)	2	Vendor-Retailer	Stackelberg Game	Perfect Information	Parametric Analysis	No
Esmaeili et al. (2009)	2	Manufacturer-Retailer	Stackelberg Game	Perfect Information	Sensitivity Analysis	No
Yu et al. (2009a)	Multi-player	Manufacturer-Retailers	Stackelberg Game	Asymmetric Information	Sensitivity Analysis	No
Wong et al. (2009)	Multi-player	Supplier-Retailers	Nash eq. and Stackelberg Game	Perfect Information	Numeric Simulations	No
Yu et al. (2009b)	Multi-player	Vendor-Retailers	Stackelberg Game	Asymmetric Information	Sensitivity Analysis	No
Esmaeili and Zeephongsekul (2010)	2	Seller-Buyer	Stackelberg Game	Asymmetric Information	Sensitivity Analysis	No
Barari et al. (2012)	2	Producer-Retailer	Stackelberg Game	Perfect Information	Evolutionary Game	Yes
Bai and Sarkis (2016)	Multi-player	Focal Organization-Suppliers	Nash eq. and Stackelberg Game	Perfect Information	Parametric Analysis	No
Esmaeili et al. (2016)	2	Manufacturer-Retailer	Stackelberg Game	Perfect Information	Evolutionary Game	Yes
Mahmoudi and Rasti-Barzoki (2018)	2	Government-Producer	Stackelberg Game	Perfect Information	Evolutionary Game	Yes
Taleizadeh et al. (2020)	3	Manufacturer, Retailer and Third party	Stackelberg Game	Perfect Information	Fuzzy theory	Yes
Yadav et al. (2021)	2	Seller-Buyer	Stackelberg Game	Perfect Information	Sensitivity Analysis	No
This paper	2	Raw Material Supplier-Manufacturer	Stackelberg Game	Asymmetric Information	Full factorial experimental design	Yes

To summarize the literature, although vendor-buyer Stackelberg models are studied in the literature, applications in the supply chain are quite limited in an asymmetric information environment. (Raj et al., 2021; Jolai et al., 2021; Ranjbar et al., 2021). As far as is known, the Stackelberg game approach aiming to reach optimal environmental expenditures as well as the optimal lot size and sales price in the green supply chain contingent on asymmetric information has not yet been researched. This study will close this gap by addressing the asymmetric Stackelberg game with environmental aspects in the vendor-buyer supply chain. Since asymmetric information better reflects the real-life problem, our main contribution is to obtain results closer to real life where the environmental concerns are increasing. In addition, today, when plastic pollution has turned into a big problem, this study presents a roadmap by addressing this problem with two scenarios, showing how much profit can be made by producing and marketing the product in an environmentally friendly way for both supplier and producer. Moreover, the interactions between parameters are investigated with the experimental design approach.

3. Problem Definition

In this section, a Stackelberg game methodology peculiar to incomplete information structure is proposed between a raw material seller and a producer. We consider a product which has a single raw material and green-sensitive demand. In this model, the producer is in a position to bear the cost of green production and marketing activities to meet the green-sensitive demand, and if the producer refuses to bear the cost of green production, he has to bear the penalty imposed by the government. The term green burden is defined in order to integrate the cost to be incurred for environmentally friendly production or the cost that will appear as a penalty if this environmental production cost is not incurred, as in Barari et al. (2012). In the proposed model, the producer does not know any cost of the raw material supplier, and the raw material supplier does not know the exact product demand, and he only knows the price elasticity of demand (a) and the greening elasticity of demand (b). Due to the asymmetry of the model, the players try to maximize their profits based on the estimations of unknown values for themselves. In this Stackelberg game methodology, the raw material supplier is the leader and determines the sales price of the raw material and the lot size. The producer is the follower who decides the selling price of the commodity and the environmental cost that can be burdened considering the raw material cost and lot size set by the raw material seller. The overall procedure of the proposed approach is given in Fig. 1.

procedure: Proposed methodology
input: Producer's financial data (*Sales revenue, Purchasing cost, Producing cost, Marketing cost, R&D cost, Environmental cost, Ordering cost, Holding cost*), Raw material supplier's financial data (*Sales revenue, Production cost, Setup cost, Holding cost*), Penalty (*greening*)

output: Optimal solution (price of the product, lot size, profit functions, raw material sales price, profits)
begin

//Raw material supplier's decision
determine *total selling price of the raw material, lot size*
//Producer's decision
determine *selling price of the product, environmental cost*
calculate *greening cost, greening penalty, green burden*
if *greening cost* > *greening penalty*
green burden = *greening penalty*
else
green burden = *greenining cost*
calculate profit functions
output the maximum profit of the chain
end

Fig. 1 The procedure of the proposed methodology

3.1. Notation and Assumptions of the Model

The notation and formulation used in our problem are introduced in this section.

Decision Variables

v: total selling price of the raw material (₺/unit)
q: lot size (units)
p: sales price of the product (₺/unit)
e: environmental cost (₺/unit)

Parameters

a: price elasticity of demand
b: greening elasticity of demand
L: greening elasticity / price elasticity coefficient (*b/a*)
d: demand
k: demand coefficient
i: percentage of holding cost per year
u: production rate coefficient
c: setup cost (₺/unit)
m: production cost (₺/unit)
n: marketing cost(₺/unit)
o: ordering cost (₺/unit)
s: supplier's production cost
g: greening cost (₺/unit)
t: greening penalty
x: binary number equal to 1 if the firm invests in green or equal to 0 if the firm is fined.
l: green burden
y: green marketing exertion
r: research & development cost (₺/unit)

Assumptions

1. In traditional supply chains, although the buyer usually controls the lot size, this model allows the seller to decide the lot size. According to Esmaeili and Zeephongsekul (2010), this is suitable for situations when setup, inventory and storage costs of the seller are higher compared to the buyer.
2. The producer does not know the costs of the raw material supplier.

3. Although the raw material supplier knows the rate of the coefficients *a* and *b*, does not know the exact demand that is similar to Esmaeili and Zeephongsekul (2010).
4. Production always meets the demand; shortages are not allowed.
5. Only the sales price of the product and environmental costs have impact on demand. Other costs are not taken into account, such as non-environmental marketing costs.
6. The planning period is infinite.

3.2. Formulation of the Model

The demand is in inverse proportion with price, p and in direct proportion with the environmental cost, e. In terms of these variables, d is expressed in Eq. (1). The environmental cost is expressed in Eq. (2). n is the unit marketing cost, and y is a percentage of the green marketing effort in total marketing costs. g is the unit greening cost and refers to the costs arising from environmentally friendly manufacturing activity. x is a binary number that allows the firm to decide whether to bear the greening cost or the penalty in Eq. (3).

$$d = kp^{-a}e^{b} \tag{1}$$

$$e = yn + g \tag{2}$$

$$l = xgq + (1 - x)\,t \tag{3}$$

3.2.1. The Profit Functions of the Producer and the Raw Material Supplier

Both the producer and the raw material supplier aim to maximize their profits which interact with each other in the chain. The profit of the follower is affected since the leader makes the first decision and sets the lot size and price of raw material and forces the follower to comply with this decision. We consider the model proposed by Esmaeili and Zeephongsekul (2010) and integrate some costs such as greening and research and development costs and develop a model that includes environmental factors. The objective functions for both players are obtained by subtracting total expenditures from total income. The producer's aim is to determine the environmental cost and selling price of the product in an attempt to maximize his profit. The profit function for the producer (Π_M) is created by subtracting all expenses from the total income and is given in Eq. (4). The first term in the producer's profit function involves the demand of the product and the product price and refers to the total revenue from the sale. The second term refers to the purchasing cost and is found by multiplying the sales price and demand of the raw material. The third term is the production cost and the fourth term is marketing cost. The fifth and sixth terms are considered to be sustainability costs. r is the Research and Development (R&D) cost per unit product and represents the amount of research and development costs required to manufacture, design and develop a greener product and e is the unit environmental cost. The ordering cost is obtained by multiplying the order quantity d/q with the unit ordering cost o in the seventh term. The last term is the average storage cost, which is calculated as traditionally in inventory management, by multiplying the average periodical stock amount by percentage of holding cost per year and the variable cost per product. (Tersine, 1994). In the case under consideration, since production is the issue instead of purchasing, the unit variable cost is considered as the unit production cost.

By substituting Eq. (1) into Eq. (4), we obtain Eq. (5).

Producer's profit = Sales revenue - Total cost of the producer
Producer's Profit = Sales revenue - Purchasing cost - Producing cost –Marketing cost- R&D cost -Environmental cost - Ordering cost - Holding cost

$$\Pi_M(p,e) = pd - vd - md - nd - rd - ed - od/q - 0.5ivq \tag{4}$$

$$\Pi_M(p,e) = k\,p^{1-a}\,e^{b} - vkp^{-a}e^{b} - mkp^{-a}\,e^{b} - nkp^{-a}\,e^{b} - rkp^{-a}\,e^{b} - kp^{-a}\cdot e^{b+1} - okp^{-a}e^{b}\,/q - 0.5i\,vq \tag{5}$$

Eq. (6) and Eq. (7) are acquired by using the first order derivative of the producer's profit function with respect to product price and environmental cost, respectively. When Eq. (6) is substituted into Eq. (5), and the first order derivatives of Eq. (5) with respect to p and e are obtained, the optimal price, p^* and the optimal environmental cost, e^* values are obtained as in Eq. (8) and Eq. (9), respectively.

$$p = \frac{a(v + m + n + r + e + oq^{-1})}{a - 1} \tag{6}$$

$$e = \frac{b(p - v - m - n - r - oq^{-1})}{b + 1} \tag{7}$$

$$p^* = \frac{a(v+m+n+r+oq^{-1})}{a-b-1} \tag{8}$$

$$e^* = \frac{b(v+m+n+r+oq^{-1})}{a-b-1} \tag{9}$$

The supplier aims at determining the lot size and sales price of the raw material in order that his profit is maximized. The profit function of the raw material supplier is obtained by deducting production, setup and holding costs from the sales revenue. The formulation and extended version of the profit function are given in Eq. (10) and Eq. (11).

Supplier's profit = Sales revenue–Total cost of the supplier

Supplier's profit= Sales revenue – Production cost – Setup cost - Holding cost

$$\Pi_S(v,q) = vd - sd - \ cd/q - 0.5icqd/r \tag{10}$$

$$\Pi_S(v,q) \ = vkp^{-a} \ \cdot \ e^b - skp^{-a}\, e^{\,b} - ckp^{-a}\, e^{\,b}/q - 0.5isq/u \tag{11}$$

Eq. (12) and Eq. (13) are acquired by using the first order derivative of the supplier's profit function with respect to lot size and raw material sales price, respectively.

$$q^* = \sqrt{\frac{2dcu}{si}} \tag{12}$$

$$v^* = Zv_0 \tag{13}$$

Due to the fact that Eq. (11) is an increasing linear function of v, it is possible for the producer to purchase the raw material at the highest price to be determined by the raw material supplier. Therefore, multiplying v by any number greater than 1 will give the optimum, v^* (Esmaeili & Zeephongsekul, 2010). In the case of zero profit by equating to Eq. (11) to zero, v_0 is calculated as follows:

$$v_0 = s + cq^{-1} + 0.5isq(ud)^{-1} \tag{14}$$

3.3. Two-Person Stackelberg Game Model with Incomplete Information

The Stackelberg game with incomplete or asymmetric information refers to the situation where the knowledge levels of the players are not equal. Therefore, it requires the use of probabilistic models. Values that the players do not know exactly are added to the model using specific probability distributions to include vagueness. In our model, the supplier determines the sales price of the raw material and lot size that provides the maximum profit in an environment where the supplier is not aware of the demand and only knows the L value which is equal to the ratio of elasticity coefficients (b/a) that specifies the demand function. Moreover, the producer aims to find the optimal product sales price and environmental cost that maximize the profit where the producer does not know the setup (c) and production (s) costs of the supplier.

3.3.1. Expected Value of the Producer's Profit

As the producer does not know the costs of the raw material supplier, he must make the best decision for himself according to the estimated values of v^* and q^*. Therefore, the expected values of v and q within certain deviations are included into the model. E_ω refers to the expected value for producer's profit function which is given in Eq. (15). The expanded version is obtained by substituting Eq. (1) into Eq. (15) and is given in Eq. (16).

$$E_\omega(\Pi_M(p,e,v^*,q^*)) = \int \Pi_M\,(p,e,v^*,q^*) f_2(\omega) d\omega \tag{15}$$

$$\begin{aligned} E_\omega\big(\Pi_M(p,e,v^*,q^*)\big) \\ &= kp^{1-a}e^b - E_\omega(v^*)kp^{-a}e^b - mkp^{-a}e^b - nkp^{-a}e^b - rkp^{-a}e^b - kp^{-a}e^{b+1} - \frac{okp^{-a}e^b}{E_\omega(q^*)} \\ &- 0.5imE_\omega(q^*) \end{aligned} \tag{16}$$

The first order derivation of Eq. (16) with respect to p is given in Eq. (17).

$$\frac{\partial E_\omega \Pi_M(p,e,v^*,q^*)}{\partial p} = kp^{1-a}e^b[(1-a)p + aE_\omega(v^*) + am + an + ar + ae + oaE_\omega(q^*)^{-1})] \tag{17}$$

The first order derivation of Eq. (16) with respect to e is given in Eq. (18).

$$\frac{\partial E_{\omega}\Pi_{M}(p,e,v^{*},q^{*})}{\partial e} = kp - aeb - 1[bp - bE\omega(v*) - bm - bn - br - e(b+1) - ob\mathrm{E}\omega((q*)^{-1})] \tag{18}$$

When Eq. (17) and Eq. (18) are solved, p* and e* are achieved as in Eq. (19) and Eq. (20).

$$p^{*}(\omega) = \frac{a(\mathrm{E}\omega(v^{*}) + m + n + r + oE_{\omega}\,((q^{*})^{-1}))}{a-b-1} \tag{19}$$

$$e^{*}(\omega) = \frac{b(\mathrm{E}\omega(v^{*}) + m + n + r + oE_{\omega}\,((q^{*})^{-1}))}{a-b-1} \tag{20}$$

3.3.2. Expected Value of the Supplier's Profit

Conformably, *Eγ* refers to the expected value of the raw material supplier's profit function. Expected value of supplier's profit function, in case the demand is not known by the supplier, is given in Eq. (21) and Eq. (22).

$$E_{\gamma}\Pi_{S}(p^{*},e^{*},v,q) = \int \Pi_{S}\,(p^{*},e^{*},v,q)f_{1}(\gamma)d\gamma \tag{21}$$

$$E_{\gamma}\Pi_{S}\,(p^{*},m^{*},v,q) \;=\; E_{\gamma}(d)(v - c - sq^{-1} - 0.5icqr^{-1}) \tag{22}$$

The first order derivation of the profit function with respect to the lot size is given in Eq. (23) and the lot size which makes the profit function zero is given in Eq. (24). In Eq. (25), the optimal v value is given. The initial value v_0, which provides zero profit for the raw material supplier, is given in Eq. (26).

$$\frac{\partial E_{\gamma}\Pi_{S}\,(p^{*},m^{*},v,q)}{\partial q} = \;\mathrm{E}\gamma\,(d)cq^{2} - si\,/\,2u \tag{23}$$

$$q^{*}(\gamma) = \sqrt{\frac{2E_{\gamma}(d^{*})cu}{si}} \tag{24}$$

$$v^{*}(\gamma) = Z^{*}v_{0}(\gamma) \tag{25}$$

$$v_{0} = c + cq^{-1} + 0.5isqE_{\gamma}(d)^{-1}u^{-1} \tag{26}$$

3.4. Supplier Stackelberg Model with Incomplete Information

In the Supplier Stackelberg game, supplier is in the leading position and makes the first decision. Supplier primarily decides the lot size and the selling price of the raw material in a way to maximize his profit. The producer is in the follower position, and after the supplier determines the lot size and the raw material sales price, the producer shapes the sales price of the product and the environmental cost that maximizes his profit. The objective function and constraints for the producer are given in Eq. (27) and Eq. (28).

max $E\omega\ \Pi_S(p, e, v^*, q^*)$

subject to

$$p^{*} = \frac{a(v + m + n + r + oq^{-1})}{a-b-1} \tag{27}$$

$$e^{*} = \frac{b(v + m + n + r + oq^{-1})}{a-b-1} \tag{28}$$

The first order derivatives of Eq. (21) with respect to q and v are given in Eq. (29) and Eq. (30) respectively.

$$\left(\frac{o+c}{q^{2}}\right)E_{\gamma}D(p^{*},e^{*}) - 0.5isu^{-1}=0 \tag{29}$$

$$\left(\frac{o+c}{q^{2}}\right)E_{\gamma}\left(\frac{\partial D(p^{*},e^{*})}{\partial v}\right)\left(v - s - \frac{c}{q}\right) + 0.5isu^{-1} = 0 \tag{30}$$

$$\frac{\partial D(p^*,e^*)}{\partial v} = \frac{(b-a)D(p^*,e^*)}{(v+m+n+r+oq^{-1})} \quad (31)$$

The first order derivative of the demand function is given in Eq. (31). After some simplification and expansion operations using Eqs. (27)-(31), Eq. (32) and Eq. (33) are obtained. It is very difficult to solve these equations by integration method. Simpson's rule is a practical method used for converting equations containing numerical integration into a non-integral structure and achieving quick results. When the Simpson's Quadrature rule is applied to Eq. (32) and Eq. (33), the optimal *v* and *q* values are reached easily (Esmaeili & Zeephongsekul, 2010).

$$\left(\frac{o+c}{q^2}\right) k \int_0^1 L^b (v+m+n+r+oq^{-1})^{b\left(1-\frac{1}{L}\right)} \left((1-L)-\frac{L}{b}\right)^{b\left(\frac{1}{L}-1\right)} f_1(b)db - 0.5isu^{-1} = 0 \quad (32)$$

$$\left(\frac{o+c}{q^2}\right)(v-s-cq^{-1}) \frac{\left(1-\frac{1}{L}\right)}{(v+m+n+r+oq^{-1})} k \int_{-1}^1 bL^b (v+m+n+r+oq^{-1})^{b\left(1-\frac{1}{L}\right)} \left((1-L)-\frac{L}{b}\right)^{b\left(\frac{1}{L}-1\right)} f_1(b)db + 0.5isu^{-1} = 0 \quad (33)$$

4. Case Study

We consider a real-life application of a Stackelberg game theory model between the raw material supplier and the producer of the plastic plugs that has a single raw material which is plastic. In the Stackelberg game model developed, the supplier determines the optimal raw material sales price and lot size as the leader. Considering these decisions, the producer decides the sales price and environmental cost of the product to get maximum profit as a follower. The producer is one of the prominent producers of the hydraulic-pneumatic components in İzmir, Turkey and supplies the plastic raw material in a granular form, processes and sells it directly to the end user. The company plans to adapt the recycling system and uses it to recycle plastics, which are production wastes. The selling price of the commodity is detected by the producer by considering the costs and the demand. The demand is sensitive to the price of the commodity and environmental costs since these criteria are considered to be effective in purchasing decisions of consumers at the present time.

Plastic takes up a lot of space in nature and generally when it is used once, it is never used again. Disposed plastic can be found in nature without dissolving for many years. The plastic materials left to the nature constitute a serious part of the environmental pollution problem. According to the World Wildlife Fund [WWF] (2018)'s report, 95% of the waste in the Mediterranean Sea is plastic. As a main factor in environmental pollution, a plastic product is selected for this study.

After testing the Stackelberg game on real data, experimental design method is used to investigate to show how the changes in parameters affect the results.

4.1. Numerical Analysis

We examine the relationship between a producer operating in the hydraulic-pneumatic industry and a plastic raw material provider. The product is a navy conical plug, which is a special product and has a single raw material. Firstly, *v, q, p* and *e* values which make maximum profit for the raw material supplier and the producer are found using Equations (27)-(33). Then, with the experimental design approach, the effects of some changes of the parameters on the *v, q, p, e, g* values and the profit functions are observed. Traditionally, sensitivity analysis is applied on continuous deterministic systems and cannot be directly applied to stochastic / probabilistic systems (Gunawan et al., 2005). Since sensitivity analysis cannot be applied in discrete and probabilistic systems, experimental design is chosen as the analysis method as it gives more successful results in such systems. Optimal product price, environmental cost, raw material selling price and lot size are determined and in optimal state, the revenues of both the producer and the raw material supplier are calculated using MATLAB R2018b and the experimental design is performed using the Minitab 14 software.

4.1.1. Scenario A: With Environmental Expenditures

It is the case the enterprise, which generates some plastic waste in the production of plastic plugs, recycles these wastes and includes them in reproduction. The total expenses were provided from the producer on a monthly basis. By defining mean *c*, *s* and *b* values which are unknown to the raw material seller and the producer, with a uniform distribution with standard deviations, the uncertainty of the model is provided. The base parameter's values such as k, i and u are obtained from Esmaeili and Zeephongsekul (2010). The greening penalty value is acquired by Turkish Environmental Law No. 5909. (2019). The other values are obtained from company officials. If customers are more environmentally conscious, demand elasticity of the greening effort is higher (Ranjbar et al., 2021). In this case study, an environment in which customers are highly environmentally conscious is assumed. For this reason, the L value, which gives the ratio of greening elasticity to price elasticity, is determined as 0.51. The parameters for the current situation are given in Table 2.

Table 2
Parameters for the current situation

k	3500	σ_c	0.01
o	0.002	$\bar{s}$	0.035
i	0.1	σ_s	0.001
u	1.01	$\bar{b}$	3.14
m	0.05	σ_b	0.05
n	0.0033	Z	1
r	0.0026	Y	0.2
L	0.51	t	72197
$\bar{c}$	0.0014		

The results obtained are provided in Table 3. As we see in Table 3, the optimal lot size is 235.0973, the raw material selling price is ₺0.0801, the product selling price is ₺0.4154, the environmental cost is ₺0.2118, and the greening cost which is obtained by omitting the environmental marketing cost from the total environmental cost is ₺0.2111. The environmental cost to be incurred which arises from green manufacturing activities such as the cost of processing recycled materials is found to be ₺49.608 which is a quite small number compared to the penalty cost. In this case, it is much more sensible for the producer to recycle the product wastes and use them as raw materials rather than endure the penalty by throwing them into nature. Considering these costs, the profit of the raw material supplier is found as ₺269.134, while the producer's profit is ₺403.136.

Table 3
Results for Scenario A

q	v	p	e	g	l	D	Π_M	Π_S	Π_T
235.0973	0.0801	0.4154	0.2118	0.2111	49.608	5977.6	₺403.136	₺269.134	₺672.270

4.1.2. Scenario B: Without Environmental Expenditures

Considering that the company does not use recycled products and sells production waste, a three-echelon supply chain is formed. However, since there is no environmental production, environmental expenditures become zero. In addition, an amount of income increase with the sale of production wastes occurs. The value of plastic waste per piece is ₺ 0.02. Since there are no environmental costs, it is assumed that demand is only sensitive to the price. For ease of calculation, it is assumed that the demand for the product and the demand for plastic waste are the same. In this scenario, it is seen that the selling price of the product is high, and the demand is low. Therefore, the profit of both the producer and the supplier is quite low compared to the other scenario. Another noteworthy issue is that the supplier, which is in leading position, earns more than the producer as usually expected in Stackelberg game. Moreover, it is observed that green activities create more demand and result in more profit, even if the recycling cost is greater than the cost of selling scrap plastics. All the results obtained are provided in Table 4 from Scenario B.

Table 4
Results for Scenario B

q	v	p	e	g	D	Π_M	Π_S	Π_T
9.393	0.652	2.1	0	0	36.2614	₺ 14.933	₺ 20.7001	₺ 35.6339

4.1.3. Experimental Design

A full factorial experimental design with three factors each consisting of three levels is created at α=0.05 significance level for the lot size, raw material sales price, the product price, the environmental cost, the greening cost, profit functions of the raw material supplier and the producer, and the total profit. The supplier's setup and production costs which are unknown to the producer and the greening elasticity of demand coefficient, which are unknown to the supplier, are determined as the factors. The reason of selecting these factors is that these factors are not exactly known by players and have the power to affect all the results. Factors are analyzed at three levels as relatively small, medium and large magnitudes. Because of the non-linear nature of the problem, it is not possible to perform the experiment with evenly spaced values in the feasible solution region. Therefore, the real-life values of these factors given in previous current situation analysis and the values close to them have been taken into consideration. The other parameters are kept the same as in the given case study. The values of these factors at each level are given in Table 5. In Table 6, the full factorial experimental design with 3 factors and 3 levels and 3^3treatment conditions are given.

Table 5
Values of factors at each level

		Factors		
		$\bar{c}$	$\bar{s}$	$\bar{b}$
Levels	0^{th} Level	0.0011	0.028	3.08
	1^{st} Level	0.0014	0.034	3.12
	2^{nd} Level	0.0016	0.035	3.14

Table 6
The full factorial design

Treatment Condition	$\bar{c}$	$\bar{s}$	$\bar{b}$
1	0	0	0
2	0	0	1
3	0	0	2
4	0	1	0
5	0	1	1
6	0	1	2
7	0	2	0
8	0	2	1
9	0	2	2
10	1	0	0
11	1	0	1
12	1	0	2
13	1	1	0
14	1	1	1
15	1	1	2
16	1	2	0
17	1	2	1
18	1	2	2
19	2	0	0
20	2	0	1
21	2	0	2
22	2	1	0
23	2	1	1
24	2	1	2
25	2	2	0
26	2	2	1
27	2	2	2

Firstly, the design of full factorial experiments is performed for the raw material sales price. Estimated effects and regression coefficients are given in Table 7. The adjusted coefficient of determination (*R-Sq*) demonstrates the proportion that the factors explain the result. Therefore, it is preferred to having the adjusted coefficient of determination coefficient close to 1 in terms of better reflecting the performance of the model. *DF* means degrees of freedom. *Seq SS* term refers to the sequential sum of squares. The sums of squares are sequentially added to the model and used to examine the amount of variation in response data. *Adj SS* is the corrected sum of squares for different components of the model. *Adj MS* is a term that gives the ratio of *Adj SS* to degrees of freedom. The *F* value is obtained by dividing the *Adj MS* values by the mean square of the error. It is understood from Table 7 that the adjusted determination coefficient is acceptable for *v*. In addition, it is seen that only the $\bar{s}$ factor is significant. It is understood that the raw material price increases as the production cost of the supplier increases. In Table 8, Analysis of Variance (ANOVA) table is given for raw material sales price. It is seen from the ANOVA table that bilateral and triple interactions are not significant. This means that the effect of the bilateral and triple interactions on the *v* cannot go beyond the randomness. However, the main effects are statistically significant together. It can be said that there is no interaction among the average values of the supplier's setup and production costs and greening flexibility.

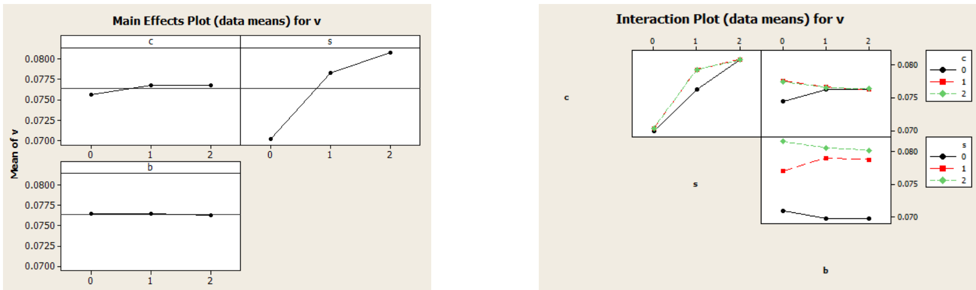
Table 7
Estimated effects and coefficients for the raw material sales price

Term	Effect	Coef	SE Coef	T	P
Constant		0.076374	0.000451	169.53	0.000
c	0.001146	0.000573	0.000552	1.04	0.312
s	0.010639	0.00532	0.000552	9.64	0.000
b	-0.00022	-0.000107	0.000552	-0.19	0.848
c*s	-0.00017	-0.000087	0.000676	-0.13	0.899
c*b	-0.00149	-0.000743	0.000676	-1.1	0.285
s*b	-0.00013	-0.000063	0.000676	-0.09	0.926
c*s*b	-0.00015	-0.000075	0.000828	-0.09	0.929
S=0.0023409		R-Sq=83.38%		R-Sq(adj)=77.26%	

Table 8
Variance analysis for the raw material sales price

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.00051549	0.00051549	0.00017183	31.36	0.000
2-Way Interactions	3	0.00000677	0.00000677	0.00000226	0.41	0.746
3-Way Interactions	1	0.00000005	0.00000005	0.00000005	0.01	0.929
Residual Error	19	0.00010412	0.00010412	0.00000548		
Total	26	0.00062642				

Fig. 2a and Fig. 2b show the main effects and the interactions for v. According to the Fig. 2, the factor that affects the raw material sales price most strongly is $\bar{s}$, followed by $\bar{c}$ and $\bar{b}$, respectively. In addition, since the lines in the graph intersect with each other, it can be concluded that interaction exists between $\bar{c}$, $\bar{s}$ and $\bar{c}$, $\bar{b}$. However, these relationships are statistically insignificant as can be seen in Table 6.



(a) Main effects for v (b) Interactions for v

Fig. 2 Main effects and the interactions plot for the raw material sales price

Table 9 shows that $\bar{c}$, and $\bar{s}$ factors are found as statistically significant for the lot size. Moreover, since the adjusted determination coefficient is 76.69%, it is concluded that these factors can explain the lot size value properly. Table 10 concludes that only the main effects are statistically significant.

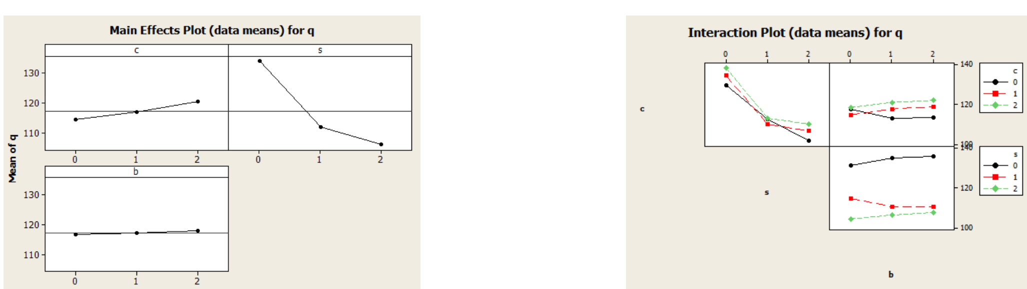
Table 9
Estimated effects and coefficients for the lot size

Term	Effect	Coef	SE Coef	T	P
Constant		117.35	1.22	96.19	0.000
c	5.74	2.94	1.407	2.09	0.048
s	-27.96	-13.98	1.494	-9.36	0.000
b	1.32	0.66	1.494	0.44	0.665
c*s	-0.48	-0.24	1.83	-0.13	0.898
c*b	3.82	1.91	1.83	1.04	0.309
s*b	-0.37	-0.19	1.83	-0.1	0.92
c*s*b	0.39	0.19	2.241	0.09	0.932
S = 6.33961		R-Sq=82.97%		R-Sq(adj)=76.69%	

Table 10
Variance analysis for the lot size

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	3674.15	3674.15	1224.72	30.47	0.000
2-Way Interactions	3	44.96	44.96	14.99	0.37	0.773
3-Way Interactions	1	0.3	0.3	0.3	0.01	0.932
Residual Error	19	763.62	763.62	40.19		
Total	26	4483.05				

Fig. 3a and Fig. 3b show that the factor with the strongest effect on q is $\bar{s}$, followed by $\bar{c}$ and $\bar{b}$ respectively. It is concluded that the unit production cost of raw material has the biggest and negative effect on the lot size. As expected, the lot size determined by the supplier is affected by the supplier's costs, but not by the greening elasticity. The 2-way and 3-way interactions exist but they are not statistically significant.



(a) Main effects for q (b) Interactions for q

Fig. 3. Main effects and interactions plot for the lot size

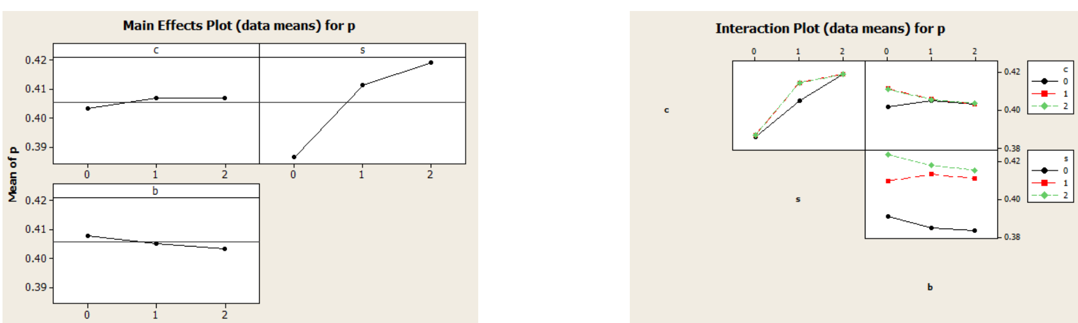
Table 11 illustrates that only factor $\bar{s}$ is statistically significant among all the factors and the interactions for the product price. The adjusted determination coefficient is consonant. Therefore, it is concluded that these factors can explain the p value properly. In Table 12, it is clearly seen that only the main effects are statistically significant together unlike bilateral and triple interactions. Fig. 4a and Fig. 4b show that the factor with the strongest effect on p is $\bar{s}$, followed by $\bar{b}$ and $\bar{c}$ respectively. It seems that the greening elasticity of demand and the price of the product are inversely proportional, although the effect of $\bar{b}$ on the price is not significant. Besides, it appears that there are interactions between the factors $\bar{c}$, $\bar{b}$ and $\bar{c}$, $\bar{s}$. However, these interactions are not statistically significant. Therefore, it can be concluded that the selling price of the product detected by producer is only affected by the production cost of the raw material.

Table 11
Estimated effects and coefficients for the product price

Term	Effect	Coef	SE Coef	T	P
Constant		0.405574	0.001383	293.16	0.000
c	0.003522	0.001761	0.001694	1.04	0.312
s	0.032633	0.016317	0.001694	9.63	0.000
b	-0.00461	-0.00231	0.001694	-1.36	0.19
c*s	-0.00052	-0.00026	0.002075	-0.12	0.902
c*b	-0.0046	-0.0023	0.002075	-1.11	0.282
s*b	-0.00055	-0.00028	0.002075	-0.13	0.896
c*s*b	-0.00045	-0.00023	0.002542	-0.09	0.93
S=0.00718868		R-Sq=83.61%		R-Sq(adj)=77.57%	

Table 12
Variance analysis for the product price

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.00494371	0.00494371	0.0016479	31.89	0.000
2-Way Interactions	3	0.00006519	0.00006519	0.00002173	0.42	0.74
3-Way Interactions	1	0.00000041	0.00000041	0.00000041	0.01	0.93
Residual Error	19	0.00098187	0.00098187	0.00005168		
Total	26	0.00599117				



(a) Main effects for p (b) Interactions for p

Fig. 4. Main effects and interactions plot for the product price

From Table 13, we can say that the adjusted determination coefficient is acceptable for the unit environmental cost of a product manufactured. In addition, it is seen that only factor $\bar{s}$ is significant. ANOVA table for the environmental cost is given in Table 14. It is seen that bilateral and triple interactions are insignificant, only the main effects are statistically significant.

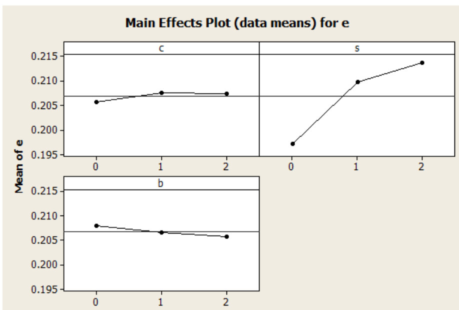
Table 13
Estimated effects and coefficients for the environmental cost

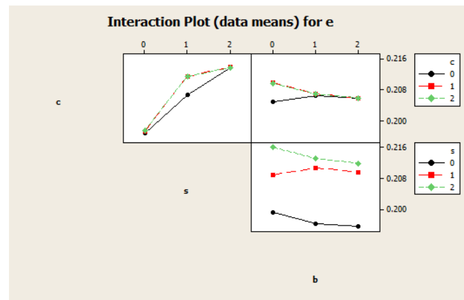
Term	Effect	Coef	SE Coef	T	P
Constant		0.206856	0.000704	293.77	0.000
c	0.0018	0.0009	0.000862	1.04	0.310
s	0.016611	0.008306	0.000862	9.63	0.000
b	-0.00236	-0.00118	0.000862	-1.37	0.188
c*s	-0.0003	-0.00015	0.001056	-0.14	0.889
c*b	-0.00232	-0.00116	0.001056	-1.1	0.286
s*b	-0.00025	-0.00013	0.001056	-0.12	0.907
c*s*b	-0.00025	-0.00013	0.001294	-0.1	0.924
S=0.00365883		R-Sq=83.61%		R-Sq(adj)=77.58%	

Table 14
Variance analysis for the environmental cost

Y	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.00128123	0.00128123	0.00042708	31.9	0.000
2-Way Interactions	3	0.00001656	0.00001656	0.00000552	0.41	0.746
3-Way Interactions	1	0.00000012	0.00000012	0.00000012	0.01	0.924
Residual Error	19	0.00025435	0.00025435	0.00001339		
Total	26	0.00155227				

Fig. 5a and Fig. 5b show that the factor with the strongest effect on *e* is $\bar{s}$ followed by $\bar{b}$ and $\bar{c}$, respectively. Furthermore, it is obvious that there are interactions between $\bar{c}$, $\bar{s}$ and $\bar{c}$, $\bar{b}$ factors. However, these interactions are not statistically significant. It is understood that the production cost of the raw material is the only factor that affects the environmental cost to be incurred among all factors examined. Such a result can be expected as the costs of raw materials increase and decrease with additional environmental processes.





(a) Main effects for *e* (b) Interactions for *e*

Fig. 5. Main effects and interactions plot for the environmental cost

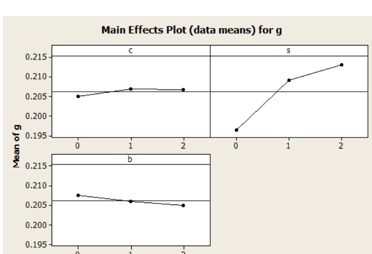
Table 15 shows that no factor and interaction are statistically significant except factor $\bar{s}$ for the greening cost. Moreover, since the adjusted determination coefficient is high, we conclude that these factors can explain the greening cost value thoroughly. It is understood from Table 16 that only the main effects are statistically significant for *g*.

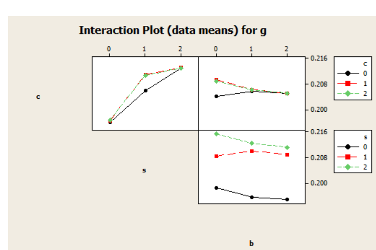
Table 15
Estimated effects and coefficients for the greening cost

Term	Effect	Coef	SE Coef	T	P
Constant		0.206181	0.000716	287.88	0.000
c	0.0018	0.0009	0.000877	1.03	0.318
s	0.016611	0.008306	0.000877	9.47	0.000
b	-0.00243	-0.00122	0.000877	-1.39	0.181
c*s	-0.0003	-0.00015	0.001074	-0.14	0.890
c*b	-0.00232	-0.00116	0.001074	-1.08	0.294
s*b	-0.00025	-0.00013	0.001074	-0.12	0.909
c*s*b	-0.00025	-0.00013	0.001316	-0.1	0.925
S=0.00372157		R-Sq=83.16%		R-Sq(adj)=76.96%	

Table 16
Variance analysis for the greening cost

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	0.00128291	0.00128291	0.00042764	30.88	0.000
2-Way Interactions	3	0.00001656	0.00001656	0.00000552	0.4	0.756
3-Way Interactions	1	0.00000013	0.00000013	0.00000013	0.01	0.925
Residual Error	19	0.00026315	0.00026315	0.00001385		
Total	26	0.00156274				





(a) Main effects for *g* (b) Interactions for *g*

Fig. 6. Main effects and interactions plot for the greening cost

Fig. 6a and Fig. 6b show that the factor with the strongest effect on g is $\bar{s}$ followed by $\bar{b}$ and $\bar{c}$, respectively. Besides, it is seen that there are interactions between $\bar{c}$, $\bar{s}$ and $\bar{c}$, $\bar{b}$ factors. However, these interactions are not statistically significant. Similar to the environmental cost, the greening cost which determined by producer is only affected by the raw material production cost significantly. Greening cost give similar results with the environmental cost as it constitutes an important part of environmental cost. From Table 17, it is seen that the adjusted determination coefficient is relatively low. The reason for this is that due to the structure of the incomplete game models, the $\bar{s}$ and $\bar{c}$ coefficients that affect the profit function of the raw material supplier are not fully known. In addition, it is seen that only factor $\bar{s}$ is significant as obtained in the previous results. ANOVA results for supplier's profit are given in Table 18. It is seen that bilateral and triple interactions are not significant.

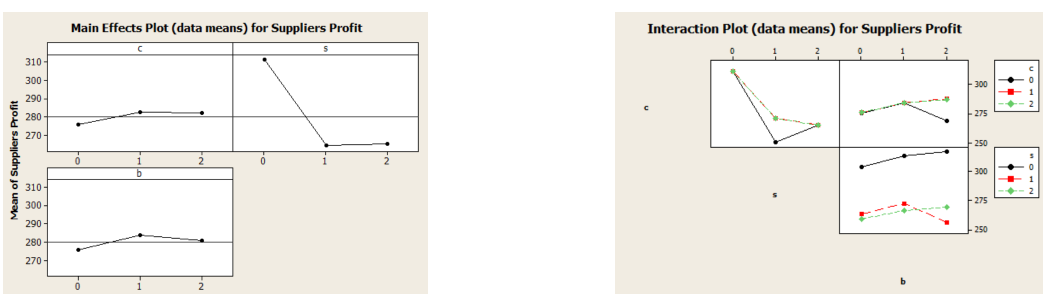
Table 17
Estimated effects and coefficients for the supplier's profit

Term	Effect	Coef	SE Coef	T	P
Constant		280.2	3.378	82.94	0.000
c	6.5	3.25	4.138	0.79	0.442
s	-46.07	-23.04	4.138	-5.57	0.000
b	5.26	2.63	4.138	0.64	0.532
c*s	0.06	0.03	5.067	0.01	0.995
c*b	8.69	4.34	5.067	0.86	0.402
s*b	-1.2	-0.6	5.067	-0.12	0.907
c*s*b	0.55	0.28	6.206	0.04	0.965
S=17.5542		R-Sq=63.3%		R-Sq(adj)=49.78%	

Table 18
Variance analysis for the supplier's profit

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	9866.4	9866.41	3288.8	10.67	0.000
2-Way Interactions	3	230.8	230.78	76.93	0.25	0.861
3-Way Interactions	1	0.6	0.61	0.61	0.000	0.965
Residual Error	19	5854.8	5854.83	308.15		
Total	26	15952.6				

Fig. 7a and Fig. 7b show that the factor with the strongest effect on supplier's profit is $\bar{s}$ followed by $\bar{c}$ and $\bar{b}$, respectively. Furthermore, it is seen that there are interactions among all the factors. However, these interactions are not statistically significant.



(a) Main effects (b) Interactions

Fig. 7. Main effects and interactions plot for the supplier's profit

Table 19 shows that no factor and interaction are statistically significant except factor $\bar{s}$ for the producer's profit. Moreover, since the adjusted determination coefficient is conformable, it is concluded that these factors can explain the producer's profit function thoroughly. It is understood from Table 20 that only the main effects are statistically significant for the producer's profit.

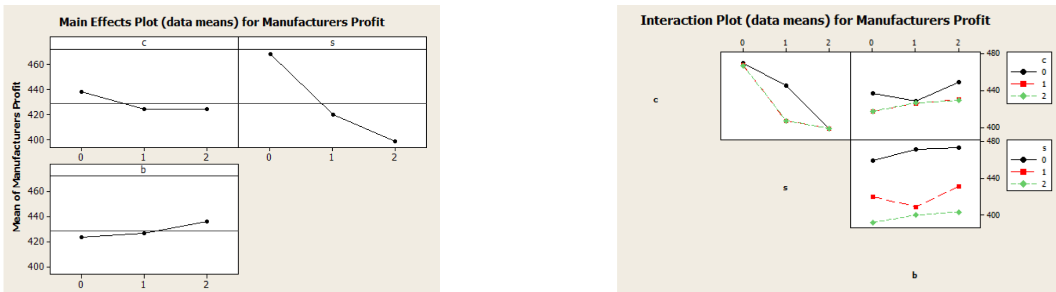
Table 19
Estimated effects and coefficients for the producer's profit

Term	Effect	Coef	SE Coef	T	P
Constant		428.58	3.204	133.75	0.000
c	-13.73	-6.86	3.925	-1.75	0.096
s	-69.74	-34.87	3.925	-8.88	0.000
b	12.4	6.2	3.925	1.58	0.131
c*s	1.33	0.67	4.807	0.14	0.891
c*b	0.06	0.03	4.807	0.01	0.995
s*b	-1.52	-0.76	4.807	-0.16	0.876
c*s*b	1	0.5	5.887	0.09	0.933
S=16.6505		R-Sq=81.65%		R-Sq(adj)=74.89%	

Table 20
Variance analysis for the producer's profit

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	23425.3	23425.3	7808.42	28.17	0.000
2-Way Interactions	3	12.3	12.3	4.1	0.01	0.997
3-Way Interactions	1	2	2	2.01	0.01	0.933
Residual Error	19	5267.5	5267.5	277.24		
Total	26	28707.1				

Fig. 8a and Fig. 8b illustrate that the factor with the strongest effect on producer's profit is $\bar{s}$ followed by $\bar{c}$ and $\bar{b}$ factors, respectively. Moreover, it appears that there are interactions among all the factors. However, these interactions are not statistically significant.



(a) Main effects (b) Interactions

Fig. 8. Main effects and interactions plot for the producer's profit

From Table 21, we see that the adjusted determination coefficient is considerably high for the complete profit of the green supply chain. In addition, it is seen that only factor $\bar{s}$ is significant similarly as in the previous results. In Table 22, ANOVA results are given for the total profit of the chain. It is seen that bilateral and triple interactions are not significant, while only the main effects are statistically significant.

Table 21
Estimated effects and coefficients for the total profit

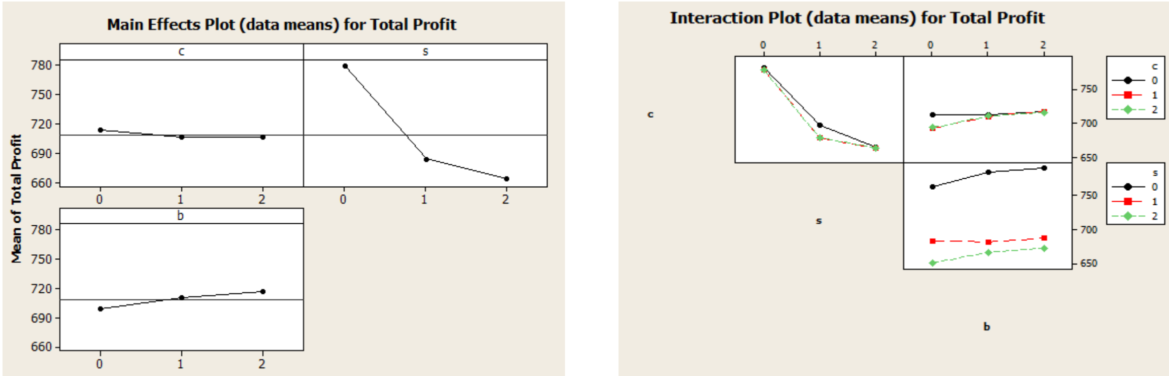
Term	Effect	Coef	SE Coef	T	P
Constant		708.78	4.535	156.3	0.000
c	-7.23	-3.61	5.554	-0.65	0.523
s	-115.81	-57.91	5.554	-10.43	0.000
b	17.66	8.83	5.554	1.59	0.128
c*s	1.39	0.7	6.802	0.1	0.919
c*b	8.75	4.38	6.802	0.64	0.528
s*b	-2.72	-1.36	6.802	-0.2	0.844
c*s*b	1.55	0.78	8.331	0.09	0.927
S=23.563		R-Sq=85.51%		R-Sq(adj)=80.17%	

Table 22
Variance analysis for the total profit

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	3	61992.8	61992.8	20664.3	37.22	0.000
2-Way Interactions	3	257.9	257.9	86	0.15	0.925
3-Way Interactions	1	4.8	4.8	4.8	0.01	0.927
Residual Error	19	10549	10549	555.2		
Total	26	72804.6				

Fig. 9a and Fig. 9b illustrate that the factor with the strongest effect on total profit of the green supply chain is $\bar{s}$ followed by $\bar{b}$ and $\bar{c}$, respectively. Furthermore, it is seen that there are interactions among all the factors except $\bar{s}$ and $\bar{b}$ factors. However, these interactions are not statistically significant.

In all the experiments, the most influencing factor that affects the results is found as the supplier's production cost ($\bar{s}$). This factor is the only factor that is significant for all results. Since this value is known by the supplier and unknown by the producer, the producer may ask the supplier to share information in order to gain more profit and reduce uncertainty. Apart from this factor, only the setup cost factor ($\bar{c}$), is significant for the lot size. Additionally, except supplier's profit, all experimental results can be explained by the factors considered. Setup cost is an information that only the supplier knows, and it is seen in the experiments that it is effective in the decisions made by the producer. Therefore, it can be concluded that especially the producer can increase his profit more in case of information sharing.



(a) Main effects (b) Interactions

Fig. 9. Main effects and interactions plot for the total profit

5. Conclusion

In this study, a Stackelberg model based on asymmetric information has been developed. The asymmetric information model implies that the seller and buyer have different levels of knowledge. Nowadays, the positions of the suppliers in the chain gain importance owing to many applications such as vendor managed inventory. Therefore, in most current studies, suppliers can be seen as leaders (Ferrara et al., 2017; Raj et al., 2021; Wu et al., 2017; Wu et al., 2021). In this study, in line with this point of view, a supply chain model in which the supplier is the leader by making the first decision and the producer is the follower is discussed. In our case, the raw material supplier is not aware of the demand function coefficients and the producer is not aware of the costs incurred by the raw material supplier. The objective of this model is to maximize the complete profit of the two-stage green supply chain. In the proposed model, as the leader, the supplier determines firstly the batch size and the raw material sales price and then the producer obtains the sales price of the product and the environmental cost that can be incurred according to these values.

The model is illustrated with two scenarios based on real data in which environmental expenditures are present and not, and changes in the model have been observed by alterations of some significant parameters with experimental design for 27 scenarios. It is concluded that the production of recycled products is much more profitable for both the producer and the supplier than the production of non-environmental product. Experiments show that uncertain factors affect the producer more than the raw material supplier. If information sharing is used to reduce this effect, it may be possible for both the producer and the raw material seller to gain more profit. Besides, it is seen that the most influencing factor for both the producer and the raw material supplier is the supplier's production cost. In the case of information sharing, if this factor is taken into consideration first, more effective results can be obtained. In the further studies, this work can be extended to include a multi-stage supply chain model which contains an end customer and more suppliers. Thus, the current complex supply chain network structures can be modeled precisely. Additionally, rather than the producer, in the future studies, it may come to the fore that the supplier also has environmental objectives. Also, with addition of social factors, a sustainable supply chain model can be provided.

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