DOKUZ EYLÜL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

A GAME THEORETICAL APPROACH FOR A GREEN SUPPLY CHAIN AND AN APPLICATION IN HYDRAULIC-PNEUMATIC INDUSTRY

by

Tuğçe DABANLI

July, 2019

İZMİR

A GAME THEORETICAL APPROACH FOR A GREEN SUPPLY CHAIN AND AN APPLICATION IN HYDRAULIC-PNEUMATIC INDUSTRY

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"A GAME THEORETICAL APPROACH FOR A GREEN SUPPLY CHAIN AND AN APPLICATION IN HYDRAULIC-PNEUMATIC INDUSTRY"** completed by **TUĞÇE DABANLI** under supervision of **ASSOC. PROF. DR. DERYA EREN AKYOL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

The development of the technology and globalization made it necessary for companies to adapt to the increasing competition conditions. As the sales prices are taking shape according to the market conditions, it is a big plus for the companies to produce a product at the same standard with low cost. At this point, the importance of the supply chain, which includes many activities that do not add value to the product, is revealed and the right management of it becomes significant.

Another issue that comes up with the increasing number of enterprises and the technological advancement is environmental pollution. Models to reduce environmental pollution have started to appear frequently in supply chains.

Supply chains consists of many elements in different echelons from the acquisition of the raw material to the delivery to the end user. The Stackelberg game, which includes the first decision-maker who is called “leader” and the other players who are called “followers” and who are required to adapt to leader’s decision, is suitable for applying to the supply chains due to this multistage structure.

In this study, a Stackelberg game is designed in which a manufacturer is the leader and a supplier is the follower. While the goal of the game for the manufacturer is to reach the optimum sales price and environmental cost, the goal of the game for the supplier is to reach optimum lot size and raw material sales price. The results are analyzed by design of experiments (DOE).

Keywords: Game theory, supply chain management, Stackelberg game, sustainability

YEŞİL TEDARİK ZİNCİRİNDE BİR OYUN TEORİSİ YAKLAŞIMI VE HİDROLİK-PNÖMATİK SEKTÖRÜNDE BİR UYGULAMA

ÖZ

Teknolojinin ve küreselleşmenin gelişimi, şirketlerin artan rekabet koşullarına adapte olmalarını gerekli kılmıştır. Satış fiyatları piyasa koşullarına göre şekillendiğinden, şirketler açısından aynı standartta bir ürünü daha düşük maliyetle üretmek büyük bir artıdır. Bu noktada, ürüne değer katmayan pek çok faaliyeti içeren tedarik zincirinin önemi ortaya çıkmakta ve doğru yönetimi önem kazanmaktadır.

Artan işletme sayısı ve teknolojik gelişme ile gündeme gelen bir diğer konu çevre kirliliğidir. Tedarik zincirlerinde çevre kirliliğini azaltmaya yönelik modeller sıkça görülmeye başlanmıştır.

Tedarik zincirleri, hammaddelerin elde edilmesinden son kullanıcıya teslimine kadar olan süreçte farklı kademelerde birçok eleman içerir. "Lider" olarak adlandırılan ilk karar vericiyi ve "takipçiler" olarak adlandırılan ve liderin kararına uyması gereken diğer oyuncuları içeren Stackelberg oyunu, bu çok kademeli yapı nedeniyle tedarik zincirlerinde uygulamak için uygundur.

Bu çalışmada, bir üreticinin lider ve bir tedarikçinin takipçi olduğu bir Stackelberg oyunu tasarlanmıştır. Üretici için oyunun amacı ürünün optimum satış fiyatına ve çevresel maliyete ulaşmak iken, tedarikçi için oyunun amacı optimum parti büyüklüğüne ve hammadde satış fiyatına ulaşmaktır. Sonuçlar deney tasarımı (DOE) ile analiz edilmiştir.

Anahtar Kelimeler: Oyun teorisi, tedarik zinciri yönetimi, Stackelberg oyunu, sürdürülebilirlik

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CHAPTER ONE
INTRODUCTION

With a stupendous growth in trade, firms have found themselves in a fierce competition. While the number of firms and product variety is increasing rapidly, standing in the market is only possible by minimizing the costs. At this point, it is key to provide the coordination of the supply chain to minimize the costs. Today, increasing uncertain market conditions also increase the importance of the supply chain to which companies are associated. Therefore, the position of the companies in the supply chain and the roles they play must be established decently to gain competitive edge (Hugos, 2002).

Thinking companies independent of each other has become impossible since there is a holistic approach in the supply chain. The companies are connected to each other in all respects. Therefore, their success has not only become dependent on themselves, but it has been influenced by all the companies in the chain. The game theory is a decision-making approach that aims to maximize the benefit of all the individuals in the game, not to maximize the benefit of an individual solely. In other words, it aims to maximize the total benefit of the individuals. Inevitably, the application of game theory in the supply chain is prosperous.

Game theory is widely used in the supply chain in two basic concepts. These are cooperative and non-cooperative game theoretical approaches. In the non-cooperative game theory, the situations in which the players do not collobrate are examined, whereas in cooperative game theory, the players' reconciliation is examined. Cooperation in the supply chain is always a great advantage for companies in the chain, but cooperation is not always possible among companies. Stackelberg game is a non-cooperative sequential game theoretical approach. That is, the players do their moves in a specific order, not simultaneously. In the Stackelberg game, there is a leader who makes the first move and a follower who observes the first players’ move and makes its move.

Supply chain is a process that includes the procuration of raw materials, processing it and distribution of it as a end product to the customer. This process inherently involves upstream and downstream activities. The term upstream represents the raw material flow to a producing company in a chain, while the activities such as distribution and marketing which are done by the firms located in the chain after the manufacturer are referred as downstream (Waters, 2003). Supply chain is suitable for modeling with the Stackelberg game due to this structure in echelons.

Another consequence of the product and firm diversity and the globalization is the significant increase in environmental pollution. In recent years, the search for a solution to this problem has accelerated. The search for solutions with mathematical modeling is often encountered. One of these mathemetical modeling methods is game theory. According to Clemhout & Wan (1991), most of the environmental incidents are interactive, dynamic and game theoretic by definition.

1.1 Aim of the Thesis

This thesis focuses on the game theory approach in a green supply chain which consists of a raw material supplier and a producer. The aim of this approach is to maximize both the manufacturer's and supplier's profit functions using Stackelberg equilibrium. In the literature, vendor-buyer models aiming to find the optimum marketing cost are common. (Esmaeili, Aryanezhad, & Zeephongsekul, 2009; Yu, Huang, & Liang, 2009). The difference of this model is that the Cobb-Douglas demand equation contains environmental expenses instead of marketing expenditures. There are also some studies based on the symmetric information structure that include both marketing and environmental expenses in demand function (Barari, Agarwal, Zhang, Mahanty, & Tiwari, 2012). In this context, marketing cost is not included in demand function since only the manufacturer and raw material supplier exist in the chain. To the best of our knowledge, this is the first study modeled with the Stackelberg game that contains asymmetric information and environmental concerns in the plastics industry.

The purpose of this study is to to reach the optimum price of the product and environmental expenditure for the manufacturer, and the optimum lot size and the raw material sales price for the supplier by producing a model including environmental costs in which the stakeholders do not have certain information about each other which is suitable for the real-life problem.

1.2 Outline of the Thesis

This thesis consists of six chapters and the contents of the chapters are as follows:

In chapter two, a detailed literature review is given. First of all, definitions of game theory and supply chain management are made. The classification of game theory and the operations of the supply chain are discussed. Subsequently, major studies on game theory approaches in the supply chain and green supply chain are compiled to date. Finally, a table demonstrating our difference with similar studies is presented.

In chapter three, we describe the problem and offer a solution methodology. Models with incomplete information are presented and a Stackelberg approach in which the supplier is the leader is developed. Then a numerical example is given to illustrate the proposed methodogy. Finally, the alteration on the results originating from the change of some parameters are observed.

In chapter four, an application in the hydraulic-pneumatic industry is conducted. Firstly, the current situation is analyzed. Values that maximize the profits of both players are reached. Then, by designing a full factorial experiment, the effects of the factors on the results are analyzed. It is observed which values should be altered to maximize gains.

Finally, concluding remarks are provided in chapter five. Furthermore, a perspective is presented for future studies.

CHAPTER TWO
LITERATURE REVIEW

2.1 Definition of the Game Theory

Game theory is a structure that provides making multiple interactive decisions. It aims to determine the behavior of each individual when the success of the individual depends on the preferences of the others. In game theory, individuals are called players. If each player tries to take best decisions and knows the other players are also trying to make best decisions for themselves, and if they are not sharing any information, this situation is called as non-cooperative game. On the other hand, if the players want to cooperate to increase their benefits, this is called cooperative game theory.

Although strategies based on the competitive structure are suggested by Cournot (1838) and Bertrand (1883) which can be considered as the basis of game theory, the first game theoretic study is proposed by von Neumann and Morgenstern (1944) (Leng & Parlar, 2005). The game theory is further expanded with Nash (1950a; 1950b; 1951; 1953)'s works on equilibrium, bargaining, non-cooperative and cooperative game concepts. Shapley and Snow (1950) conducted a study which examines discrete games and their solutions. In addition, Mayberry, Nash, & Shubik (1953) evaluated the efficient point, the Edgeworth, von Neumann and Morgenstern and cooperative game solutions with and without side-payments.

Aumann (1959) published a paper interested in cooperative game theory and then, examined the core concept for cooperative games without side payments in another study (Aumann, 1961). Shubik (1962) studied the profits and joint costs sharing techniques. Schmeidler, (1973) presented a study which aims to find equilibrium points of nonatomic games with Nash's equilibrium approach.

In the following years, game theory has become a widely studied field in various areas. According to Tinç (2018), some of these areas are political sciences, economics, social and individual psychology, biology, computer science, philosophy sports and politics.

The game theory can be classified in many ways. When it is desired to classify according to the mobility of the game, game theory can be divided into two branches as static and dynamic games. If the decision-making process in a game is independent of the time, this game is called static. However, if the decisions of the players vary over time, these games are called dynamic games (Wang & Parlar, 1989). A significant classification of the game theory is given in Figure 2.1.

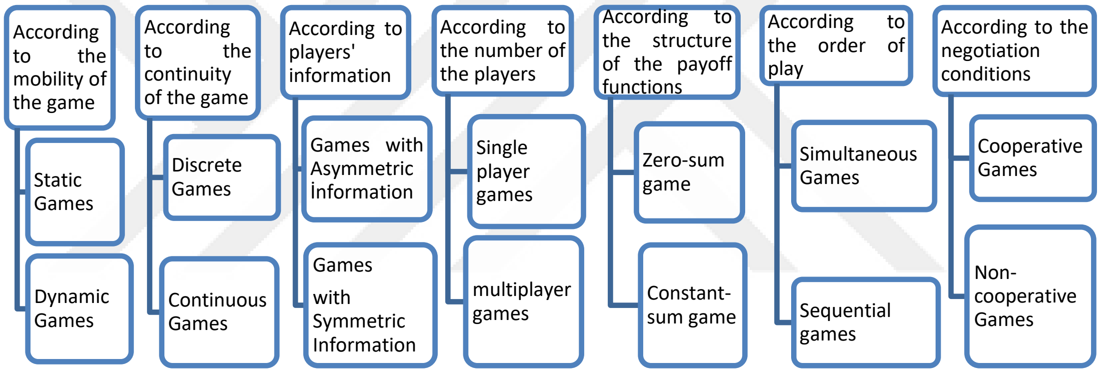

Figure 2.1 The classification of the game theory

According to the Cachon & Netessine (2006), the simplest form of the dynamic games is proposed by von Stackelberg (1934). In Stackelberg's model, a player moves first, and the second player observes the first player's move and decides. The player who makes the first move is called the leader and the second player who follows the leader is called the follower. In this game, the leader has to make the choice knowing that the follower will choose the best case for him. Accordingly, in this game, the player who makes the first move is more advantageous. This situation is known as "the first mover advantage". When the problem is analyzed with backward induction method, the best strategies are found as s_1* and $s_2*(s_1)$ for the leader and for the follower respectively. Π_1 is the payoff function of the leader. The leader reaches the value that maximizes this function in Equation (2.1). In the direction of the strategy determined by the leader, maximizing value of the follower's payoff function is given in the Equation (2.2).

$$\frac{\partial \Pi_1(s_1, s_2)}{\partial s_1} = 0 \tag{2.1}$$

$$\frac{\partial \Pi_2(s_1, s_2 * (s_1))}{\partial s_2} = 0 \tag{2.2}$$

Games which contain a limited number of players and limited moves within a limited time period are called discrete games. In continuous games, decisions are taken in a continuous period of time. Continuous models are also used in the supply chain frequently as they reflect the real life models more accurately. Differential games are typical example of continuous games.

Players' information status is an important factor in the classification of games. In the symmetric game structure, each player has complete information about other players' strategies. On the contrary, in an asymmetric informed game structure, each player does not have complete knowledge of other players' strategies. Asymmetric information significantly increases the complexity in determining the functions of the players. Therefore, despite the fact that asymmetric information structure complies with the real life problems better, it has not been used extensively to date.

One of the studies based on asymmetric information is Kagel (1996) 's study in which an ultumatum game model with asymmetric information structure is proposed. Another study which is carried out by Cardaliaguet (2007) includes a differential game with two players. In addition, a study of stochastic differential games containing asymmetric information by Cardaliaguet & Rainer (2009) is also conducted. Fershtman & Pakes (2012) examined a game theoretic model with dynamic asymmetric information. Athey & Bagwell (2001, 2008) proposed dynamic game models in which the price is known for each player but the costs are confidential.

Esmaeili & Zeephongsekul (2010) developed a supply chain model based on Stackelberg game with asymmetric information.

It is possible to differentiate the games according to the number of players. Games can be divided into single player games or multiplayer games. Single player games are decision problems and are generally not considered in the field of game theory (Tinç, 2018). Multiplayer games form the basis of game theory. As the number of players increases, the degree of complexity increases, thereby two-player games are more common in the literature. For more information about two-player games, see Rapoport (1973).

Constant-sum is the situation that the sum of the gains or losses of the players is a constant value for any decision strategy in a game. If this constant is zero, this special case is called zero-sum game.

According to the order of the moves, the games can be divided into simultaneous and sequential games. If the players are doing their moves at the same time and therefore are not aware of each other's strategies, this game is called simultaneous. If players are unable to receive information from each other, they are considered in this category even if the decisions are not taken at the same time. (Dixit, Skeath & Reiley, 2009). Battle of the sexes, chicken and prisoner's dilemma games are among the best known examples of simultaneous games.

On the other hand, if the moves are made in a certain order, this game is called sequential game. Tic-tac-toe and chess are examples of sequential games. Stackelberg game is also an example of sequential games because the game is shaped by a leader making his first move. Repeated games which players are practising their strategies when the game is proceeds are also in the category of sequential games. Also, there are some models compounds sequential and simultaneous games.

Finally, the games can be divided into two categories as coooperative and non-cooperative games. If players form their strategies independently of each other, and they do not communicate and cooperate with each other, such games are called non-cooperative games. The definition and first approach developed for reaching the solution of non-cooperative game is made for the first time by Nash (1950a; 1951).

The dynamic non-cooperative game concept is introduced by von Stackelberg (1934). Since there are many upstream-downstream elements in the supply chain such as supplier, manufacturer and wholesaler and as one of these elements makes the first decision and the others are in the following position, the Stackelberg equation takes place in SCM modeling affluently.

Stochastic game is another version of dynamic non-cooperative game. In stochastic games, the game consists of steps and these steps are interdependent with transition possibilities. Stochastic game is enhanced by Shapley (1953).

Non-cooperative game is often used in the supply chains in the past studies. However, cooperative game theory in the supply chain is becoming increasingly popular since collaboration and exchange of information are becoming more and more important in today's supply chain concept. Companies are resorting to this way to survive in the extensive competitive conditions.

Unlike the non-cooperative games, cooperative games contain players who communicate and coordinate with each other.

Bargaining game is a special version of the cooperative game teory that the players negotiate in order to achieve better results for themselves. Nash (1951) is the first to propose the bargaining game concept. Nash (1953) proposed a negotiation and an axiomatic model for the two-person cooperative game and compared the results.

The coalition formation refers to a association of a number of players due to reasons such as capacity sharing, economies of scales or competitiveness. The cooperative relations of the players forming the coalition and non-cooperative relations with the players outside the coalition are analyzed in these game theoretic models. Although coalition structures are quite appropriate for the supply chain, their implementation is very few due to its complication and difficulty in achieving the solution.

One of the first studies about the coalition formation belongs to Neumann and Morgenstern (1944). Hurwicz (1945) proposed the theory of games and the aim was to analyze the conditions and nature of coalition formation. Shubik (1952) examined theories of competition and coalition formation. Greenberg (1994) propounded a detailed research about coalition structures and its applications.

The allocation of the common profits or costs obtained in cooperative games is an important problem. The cost allocation problem emerges when individuals decide to cooperate since each individual wants to minimize his costs and maximize his profit by meeting at a common point. Cost allocation concerns how these individuals are willing to share common costs. A cost allocation problem can be transformed into a cost game. (Tijs & Driessen, 1986). Tijs & Driessen (1986) divide the cost allocation methods into two groups as methods based on marginal costs in entering coalitions and methods minimizing maximum unhappiness. Hamlen, Hamlen Jr & Tschirhart (1977; 1980) and Callen (1978) gave the first instances of implementations on cost allocation in cooperative game theory. For a fair distribution, methodologies such as Shapley Value or the Core are often used (Emir, 2014).

2.2 The Definition of the Supply Chain Management

Before the name of supply chain management (SCM) came into being, it was called "Operations Management" or “Logistics Management” (Hugos, 2002). The supply chain management term is first used in the literature by Oliver & Webber (1982). After this date, it has been involved heavily in the literature and become a concept that must be adapted immediately in order to survive in the competitive environment for companies. Cooper, Lambert, & Pagh (1997) published a study that reveals the difference between this new concept and the classical concept of logistics.

There are thousands of wide and narrow definitions of SCM. According to Ayers (2001) “Life cycle processes supporting physical, information, financial, and knowledge flows for moving products and services from suppliers to end-users.” Cooper & Ellram (1993) defines the SCM as “An integrated philosophy that manages the total flow of a distribution channel from the supplier to the end customer.”

Based on these definitions, SCM simply refers to the management of the processes which include obtaining the raw materials, designing, producing and delivering of the desired product to the customers.

The SCM aims to remove the distinction between all departments within the enterprise and to remove the distinction between companies by communication and cooperation. When the distinction between the departments of the companies is removed and the companies are evaluated as a whole with its suppliers, it is noticed that profits are increasing and firms are able to survive in the competitive environment with this integrated point of view. Therefore, the popularity of this term has been going on since its inception.

Today, because of the rapid increase in the number of firms, firms must demonstrate their differences in order to be successful. The right management of the supply chain is of great importance in terms of putting forward the differences. Decreasing process costs, reduction of wastes, ensuring the rapid flow of money and goods and providing environmental benefits are possible with a right managed supply chain.

Flow in the SCM can be physical, financial and informational. A basic supply chain model consisting of four echelons is illustrated in Figure 2.2.

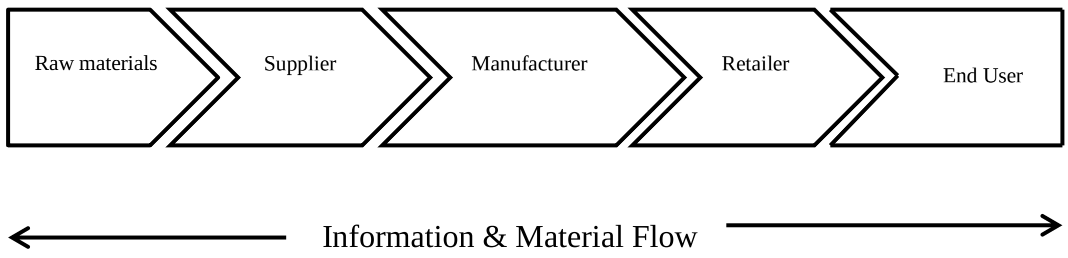

Figure 2.2 A basic illustration of a supply chain

2.3 Game Theory in Supply Chain Management

Chacko (1961)'s study may be the first study including coalition formation in supply chains. The study examines a multi-plant factory which has a variety of products and its relationship with the two distributors.

Takahashi (1964) proved that a stochastic non-cooperative n-person game has an equilibrium point. In today's market, where there is strict competition, demands, prices etc. are not only affected by the company's own situation, but also by the situation of other firms in the sector. This shows that the stochastic game theoretical methods are suitable for modeling supply chains.

Başar & Olsder (1982) conducted a broad study which explores static and dynamic non-cooperative game theory and its applications.

Parlar (1988) made one of the first studies which examines an inventory management problem with a static game theoretical approach (Cachon & Netessine, 2006).

Kohli & Park (1989) analyzed some bargaining models that include a buyer and a seller. Negotiation over lot size orders are provied by quantity discounts. Their aim is to maximize the efficiency and they examined the effect of risk sensitivity and bargaining power on the negotiated amounts.

Reyniers & Tapiero (1995) developed cooperative and non-cooperative models which aim to reduce price and after-sale costs and to maximize product quality. Further they compared the results.

Ertogral & Wu (2001) presented a repated game in which the players negotiating over the order quantity and price in a supply chain with two players and minimized the cost with the minimum network flow problem methodology.

Li, Huang, Zhu, & Chau (2002) also presented a cooperative bargaining model that provides the best solution for each player.

Granot & Sošić (2003) developed a three-stage supply chain approach that consists of a product whose demand is stochastic and they discussed the allocation of the profit among the players.

Dong, Zhang, & Nagurney (2004) developed a supply chain network equilibrium model with random demands which is analyzed through Nash equilibrium. Then, they illustrated the model through several numerical examples. According to their claims this is the first supply chain network equilibrium model with random demands.

Kemahlıoglu Ziya (2004) proposed a decentralized, two-echelon cooperative supply chain model which analyzes inventory transactions among the retailers and the supplier. Shapley value methodology is used to maximize the total profit of the coalitions.

Reinhardt & Dada (2005) modeled the problem as a cooperative game and developed an algorithm based on the Shapley Value to allocate the costs fairly.

Chen, Liang, & Yang (2006) developed an efficiency game for a one-supplier one-manufacturer supply chain model. The efficiency functions of each player are generated by Data Envelopment Analysis (DEA) and activity functions for both players are maximized by a bargaining game model.

Liang, Yang, Cook, & Zhu (2006) developed Data Envelopment Analysis (DEA) models to evaluate the efficiency of supply chain. They examined the seller-buyer interaction with a two-stage non-cooperative game in which the seller is the leader and the buyer is the follower.

Rosenthal (2008) proposed a cooperative game theoretical approach that deals with the pricing of a commodity which is sold in a coalition. Using Shapley value method, models which include complete and incomplete information are created.

Apt & Witzel (2009) used the coalition formation structure in a cooperative game model which analyzes conjoining and partition decisions.

Esmaeili et al. (2009) examined some seller–buyer supply chain models to analyze the relationships between seller and buyer with non-cooperative game which is based on the Stackelberg's strategy. They considered the case from two perspectives: the seller as the leader (seller-Stackelberg) and the buyer as the leader (buyer-Stackelberg) and presented some numerical examples.

Leng & Parlar (2009) constituted a cooperetive game model for a three-level supply chain and evaluated the five possible coalition situations. Finally, they applied an illustrating example and conducted a sensitivity analysis for the model they proposed using simulation approach.

Krajewska, Kopfer, Laporte, Ropke, & Zaccour (2008) applied a horizontal cooperative game approach, based on real data in the transportation sector. Moreover, they discussed the fair allocation of the profits among the freight carriers. As a result, they have found that freight carriers could make much more profit if they formed a coalition.

Leng & Parlar (2009) used the non-cooperative game theory approach to analyze supply chains by means of Nash and Stackelberg equilibria, adapted cost sharing contracts to the model and compared the results obtained.

Zhang (2009) developed a cooperative game theory approach for an inventory model that includes a warehouse and multiple retailers. The core method is used to ensure fair distribution of costs among the retailers.

Lovejoy (2010) developed a supply chain model consisting of multiple suppliers and one buyer, and offered a bargaining theory-based solution.

Ren, Cohen, Ho, & Terwiesch, (2010) developed two versions of a game theory model: a static non-cooperative game and a game with long term equation, and analyzed the information sharing approach. They claimthat with the version which includes long-term equilibrium forecasts more realistic results are achieved than the non-cooperative version of the game.

Zhao, Wang, Cheng, Yang, & Huang (2010) investigated the effects of coordination in a supply chain which consists of a manufacturer and a retailer. An option mechanism is developed and the coordination of the supply chain is ensured.

Parker & Kapuscinski (2011) proposed a solution methodology to a two-player supply chain model which has limited capacity and stochastic demand constraints with Markov Equilibrium approach.

Wu, Chen, & Hsieh (2012) established and analyzed the non-cooperative supply chain models composed of two retailers and one supplier. Some of these models are analyzed with Stackelberg equilibrium.

Lin & Hsieh (2012) formed a competitive coalition structure and reached Cournot or Nash equilibria with a cooperative variational inequality problem approach.

Xu, Yang, & Wang (2014) discussed a multi-person dynamic cooperative game. Fuzzy colitions were created and used the weighted Shapley value method, taking into account each player's innovation capability for the allocation of common costs.

Baykasoğlu & Özbel (2016) used the travelling salesman algorithm, which aimed to minimize the distance to minimize the total cost for school bus services. The school bus services are assigned as players of the cooperative game and Shapley value method is used to allocate the cost among the the school bus services. In the case of a coalition, they concluded that there was a remarkable cost descension for all the players in the coalition.

Modak, Panda, & Sana (2016) analyzed a supply chain that consists of a manufacturer and two retailers, with Cournot, Collusion and Stackelberg game concepts. With the nested bargaining process, they aimed to find the best result for each player. They expressed their claims by a numerical example.

Game theoretical models, especially Stackelberg game models integrated with the inventory models have been frequently used in the literature. An overview of studies that combine Stackelberg game with inventory models are provided in the Table 2.1.

Table 2.1 An overview of studies that combine Stackelberg game with inventory models

Paper	# of Players	Properties of Players	Methodology	Information Structure	Analysis method	Environmental Concerns
Viswanathan & 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. (2009)	Multi-player	Manufacturer-Retailers	Stackelberg Game	Asymmetric Information	Sensitivity Analysis	No
Wong & Leung (2009)	Multi-player	Supplier-Retailers	Nash eq. and Stackelberg Game	Perfect Information	Numeric Simulations	No
Yu, Chu, & Chen (2009)	Multi-player	Vendor-Retailers	Stackelberg Game	Asymmetric Information	Sensitivity Analysis	No
Esmaeili et al. (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 & Sarkis (2016)	Multi-player	Focal Organization-Suppliers	Nash eq. and Stackelberg Game	Perfect Information	Parametric Analysis	No
This thesis	2	Raw Material Supplier-Manufacturer	Stackelberg Game	Asymmetric Information	Full factorial experimental design	Yes

2.4 Game Theory in Green Supply Chain Management

The issue of reducing the increasing environmental pollution is debouched with industrialization. However, the game theory applications in Green Supply Chain Management (GSCM) have emerged in recent years. Generally, the use of game theory to reduce pollution involves analyzing the compliance or non-compliance of enterprises with the restrictions that central or local government imposes.

One of the first examples of the applications of game theory in the use of environmental resources is the use of fish resources. For a detailed review on the game theory models of fishery management see Kaitala (1986).

Clemhout & Wan (1991) developed a dynamic fish war game approach and compared it to the classical dynamic game theory approach involving Cournot-Nash balance.

Dockner & Van Long (1993) used cooperative and non-cooperative game theory approaches in the chain that consists of the government and the producer, to minimize the pollution level. It is assumed that in the cooperative approach, the producer complies with the pollution control agreement of the government and in the non-cooperative approach, the producer does not comply with this agreement.

Majumder & Groenevelt (2001) have modeled the competition between a manufacturer and a remanufacturer in the remanufacturing industry by creating the Nash equilibrium.

Brunner & Starkl (2004) developed a cooperative game theory approach to procure sustainable water management.

Sturm & Weimann (2006) examined the consumption of common resources with game theoretic approaches.

Zhu & Dou (2007) applied evolutionary game theory to a green supply chain consist of government and businesses.

Bernard, Haurie, Vielle, & Viguier (2008) included dynamic game theory and used the Cournot-Nash equilibrium in their study on carbon emission trade which emerges with the Kyoto protocol.

Zhao, Neighbour, Han, McGuire, & Deutz (2012) developed a game theory approach in order to reduce carbon emissions in a green supply chain in which governments and producers are involved.

Zhang & Liu (2013) implemented the Stackelberg game in a three-level green supply chain consisting of a supplier, a manufacturer and a retailer. Shapley value and the Core methods are used for the fair distribution of the revenue.

Tian, Govindan, & Zhu (2014) developed an evolutionary game theory approach and simulation model that takes into account the diffusion rate of the supply chain consisting of automobile manufacturers and the payoffs of the manufacturers.

Du, Ma, Fu, Zhu, & Zhang (2015) presented a Stackelberg game approach between the government and the company that has to comply with the emission limit set by the government in a supply chain in which emissions trading is possible.

Cao, Zhang, & Zhou (2016) organized a Stackelberg game on the carbon emission amount in a two-level supply chain consisting of a manufacturer and a retailer.

In order to reduce carbon dioxide emissions and maximize the profits, Huang, Wang, Zhang, & Pang (2016) implemented the Stackelberg game model in a supply chain that contains a manufacturer with a large number of suppliers and retailers, and utilized the genetic algorithm to achieve a solution.

Hong, Chu, Zhang, & Yu (2017) designed a Stackelberg game in which the local government is the leader and the firms are the followers in a multi-echelons supply chain. The aim of the government is the maximization of the social welfare and, the aim of the firms the maximization of the profits. In this game, companies must comply with the emission limits of the government and act accordingly.

Madani & Rasti-Barzoki (2017) formed a model in which the government is the leader in a green and a non-green supply chains.

Wang, Wang, & Huang (2017) proposed a model that 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.

Zhai, Zhang, Cheng, Zhou, & Su (2017) developed a game theory approach based on incomplete information among the farmer, the biomass power plant and the government and reached the solution with the Nash equilibrium.

Babu & Mohan (2018) adopted the evolutionary game theory approach to ensure the sustainability of the supply chain.

Moradinasab, Amin-Naseri, Behbahani, & Jafarzadeh (2018) developed a sustainable model of petroleum supply chain. They used a game theoretical multi-objective approach to gain maximum profit and minimum environmental pollution. Nash and Stackelberg equilibria are applied to gain the best results.

CHAPTER THREE
PROBLEM DEFINITION

3.1 Proposed Solution Methodology

The developed models in the literature are generally suitable for a situation in which both the players share their operational information with each other equally. However, companies often do not approach to share their information with their suppliers or other companies in the chain, mostly for reasons of competition or to protect the confidentiality of the business.

In this section, a green supply chain model consisting of a manufacturer and a raw material supplier is formulated based on incomplete (asymmetric) information structure. The cases which the manufacturer does not know the costs of the raw material supplier and the raw material supplier does not know the exact product demand and knows only the price elasticity of demand (*a)* and the greening elasticity of demand (*b)* values are taken into consideration. A model can be developed based on incomplete information taking into account the different levels of knowledge of the producer and the raw material supplier. As the manufacturer does not know the costs of the raw material supplier, the manufacturer has to make the best decision for himself according to the estimated values of the raw material sales price and the lot size. Therefore, the expected values of the raw material sales price and the lot size values within certain deviations are included in the model.

Notation

Decision Variables

v: total selling price of the raw material (₺/unit)

q: lot size (units)

p: selling price of the product (₺/unit)

e: environmental cost (₺/unit)

Parameters

a: price elasticity of the product

b: greening elasticity of the product

d: demand

k: demand coefficent

i: percentage of storage cost per year

u: production rate coefficent

c: setup cost (₺/unit)

m: manufacturing 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

- The manufacturer does not know the expenditures of the raw material supplier.
- Although the raw material supplier knows the rate of the coefficients *a* and *b*, he does not know the exact demand.
- Production always meets the demand, shortage is not allowed.

$$d = k \cdot p^{-a} \cdot e^{b} \tag{3.1}$$

$$e = y \cdot n + g \tag{3.2}$$

$$l = x \cdot g + (1 - x) \cdot t \tag{3.3}$$

The term d refers to the demand and it is expressed by Equation (3.1). The term a is the coefficient that represents the price elasticity of demand. This term is used to see what amount of change is being made on the product demand by the price change. Usually the price increase leads to a decrease in the demand. Therefore, a is expressed as negative in demand function. The term b refers to the greening elasticity of demand. Generally, the increase of the greening degree of the product causes an increase in the demand of the product. Nowadays, customers' green product buying trends are gradually increasing. Given these factors, the greening / demand coefficient is considered positive in the model. However, as the greening degree of the product increases, there is an increase in the price, which may adversely affect the demand. However, considering this situation, environmental costs are added to the profit function as an expenditure. Briefly, it can be said that the demand is in inverse proportion with price and in direct proportion with the greening cost. The factors affecting the demand of the product except for the price and the degree of greening are expressed in the model with the k coefficient.

The environmental cost is stated as e and it is expressed by Equation (3.2). 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 cost arising from a green manufacturing activity. x is a binary number that allows the firm to decide whether to bear the greening cost or the penalty in Equation (3.3).

Both the manufacturer and the raw material supplier aim to maximize their profits in the supply chain. The objective functions for both players are obtained by subtracting total expenditures from total income.

Manufacturer’s Profit = Sales Revenue of the Product – Total Cost of the Manufacturer

Manufacturer’s Profit = Sales Revenue – Purchasing Cost – Manufacturing Cost – Marketing Cost – R&D Cost – Environmental Cost – Ordering Cost – Holding Cost

$$\Pi_M\,(p,e) = p\cdot d - v\cdot d - m\cdot d - n\cdot d - r\cdot d - e\cdot d - o\cdot\frac{d}{q} - 0.5\cdot i\cdot m\cdot q \qquad (3.4)$$

The profit function of the manufacturer represented by Π_M is obtained by deducting the expenses from the gain from the product sales in Equation (3.4). *v* is a decision variable which represents total selling price of the raw material and the purchasing cost of the raw material for the manufacturer is obtained by multiplying *v* with the demand *d*.

The unit production cost is indicated by *m* and refers to the various costs such as labor, electricity, water etc. Incurred to manufacture a product. The marketing cost, *n* refers to the total cost of the marketing department of the enterprise per unit product.

The ordering cost, *o* is a fixed cost incurred when the manufacturer gives an order to the raw material supplier. The ordering cost for a period is found by multiplying this fixed value with the demand / lot size ratio. The holding cost is the average storage cost and is considered as a percentage of the production cost in the model. To reach the average value, it is multiplied by the lot size / 2.

$$\Pi_M\,(p,e) = k\cdot p^{1-a}\cdot e^b - v\cdot k\cdot p^{-a}\cdot e^b - m\cdot k\cdot p^{-a}\cdot e^b - n\cdot k\cdot p^{-a}\cdot e^b - r\cdot k\cdot p^{-a}\cdot e^b - k\cdot p^{-a}\cdot e^{b+1} - \frac{o\cdot k\cdot p^{-a}\cdot e^b}{q} - 0.5\cdot i\cdot m\cdot q \qquad (3.5)$$

Equation (3.5) is obtained by transforming the profit function of the manufacturer according to the Equation (3.1). In equation (3.6), the sales price value is obtained by taking the first order derivative of the manufacturer's profit function with respect to p and setting it to zero. Similarly, the environmental cost given in Equation (3.7) is obtained by acquiring the first-order derivative of the profit function of the manufacturer according to e and setting to zero.

$$p = \frac{a(v+m+n+r+e+o \cdot q^{-1})}{a-1} \tag{3.6}$$

$$e = \frac{b(v-m-n-r-o \cdot q^{-1})}{b+1} \tag{3.7}$$

When Equations (3.6) and (3.7) are solved together, the optimal *p** and *v** values are obtained and are given in Equations (3.8) and (3.9). The manufacturer's profit function is pseudoconcave, and it is sufficient to get the first-order derivative to find the optimal point of a pseudo-concave function. The proof of the manufacturer's profit function is pseudo-concave is given in the Appendix.

$$p^* = \frac{a(v+m+n+r+o \cdot q^{-1})}{a-b-1} \tag{3.8}$$

$$e^* = \frac{b(v+m+n+r+o \cdot q^{-1})}{a-b-1} \tag{3.9}$$

Supplier's Profit = Sales Revenue of the Raw Material –Total Cost of the Supplier

Supplier's Profit= Sales Revenue – Production Cost – Setup Cost – Holding Cost

$$\Pi_s(v,q) = v \cdot d - s \cdot d - c \cdot \frac{d}{q} - 0.5 \cdot i \cdot s \cdot q \cdot \frac{d}{r} \tag{3.10}$$

$$\Pi_S = v \cdot k \cdot p^{-a} \cdot e^b - s \cdot k \cdot p^{-a} \cdot e^b - c \cdot k \cdot p^{-a} \cdot \frac{e^b}{q} - 0.5 \cdot i \cdot s \cdot \frac{q}{u} \tag{3.11}$$

$$q^* = \sqrt{\frac{2 \cdot d \cdot c \cdot u}{s \cdot i}} \tag{3.12}$$

$$v^* = Z \cdot v_0 \tag{3.13}$$

Since the profit function is linear in *v*, the optimum *v* value can be achieved at any Z value. In the case of zero profit, the acquisition of v_0 is given in Equation (3.14).

$$v_0 = s + c \cdot q^{-1} + 0.5 \cdot i \cdot s \cdot q \cdot (u \cdot d)^{-1} \tag{3.14}$$

3.1.1 Models with Incomplete Information

3.1.1.1 Expected Value of the Manufacturer's Profit

E_ω refers to the expected value used in the manufacturer's function and $E\gamma$ refers to the expected value used in the supplier's function. Manufacturer's profit function is given in Equation (3.15). When the profit function is rearranged according to Equation (3.1), Equation (3.16) is obtained.

$$E_\omega\big(\Pi_M\ (p,e,v^*,q^*)\big) = \int \Pi_M\ (p,e,v^*,q^*) f_2(\omega) d\omega \tag{3.15}$$

$$E_\omega(\Pi_M\ (p,e,v^*,q^*) \ = \ k \ \cdot p^{1-a} \ \cdot \ e^b - E\omega(v^*) \ \cdot \ k \ \cdot p^{-a} \ \cdot \ e^b \ - \ \ m \ \cdot k \ \cdot p^{-a} \ \cdot \ e^b - n \ \cdot k \ \cdot p^{-a} \ \cdot \ e^b - r \ \cdot \ k \ \cdot p^{-a} \ \cdot \ e^b - \ k \ \cdot \ p^{-a} \ \cdot \ e^{b+1} - \ o \ \cdot \ k \ \cdot p^{-a} \ \cdot \ e^b \ / \ E_\omega\ (q^*) - 0.5 \ \cdot \ i \ \cdot \ m \ \cdot E_\omega(q^*) \tag{3.16}$$

First order derivative of Equation (3.16) with respect to *p* is given in the Equation (3.17).

$$\frac{\partial E_\omega(\Pi_M\ (p,e,v^*,q^*))}{\partial p} \ = k \cdot \ p^{1-a} \ \cdot \ e^b \ [(1-a) \cdot \ p \ + \ a \ \cdot \ \ E_\omega\ (v^*\ ) + \ a \ \cdot \ m \ \ + \ a \ \cdot \ n \ + a \ \cdot \ r \ + \ \ a \ \cdot \ e \ + \ \ o \ \cdot \ a \ \cdot \ \ E_\omega\ ((q^*)^{-1}\ )] \tag{3.17}$$

First order derivative of Equation (3.16) with respect to *e* is given in Equation (3.18).

$$\frac{\partial E_\omega(\Pi_M\ (p,e,v^*,q^*))}{\partial e} = \ k \cdot \ p^{-a} \cdot \ e^{b-1}\ [b \ \cdot \ p - b \ \cdot \ E_\omega\ (v^*) - \ b \cdot \ m - b \cdot \ n - b \ \cdot \ r - e \ \cdot (b \ + \ 1) - \ o \cdot \ b \ \cdot \ E_\omega\ ((q\ *)^{-1})] \tag{3.18}$$

When Equations (3.17) and (3.18) are solved together, p^* and e^* are achieved and are given in Equations (3.19) and (3.20).

$$p^*(\omega) = \frac{a(\mathrm{E}_{\omega}(v^*) + m + n + r + o \cdot \mathrm{E}_{\omega}((q^*)^{-1}))}{a - b - 1} \tag{3.19}$$

$$\mathrm{e}^*(\omega) = \frac{b(\mathrm{E}_{\omega}(v^*) + m + n + r + o \cdot \mathrm{E}_{\omega}((q^*)^{-1}))}{a - b - 1} \tag{3.20}$$

3.1.1.2 Expected Value of the Raw Material Supplier's Profit

Conformably to the expected value of the manufacturer's profit function, the expected value of the raw material supplier's profit function is found in Equations (3.21) and (3.22)

$$E\gamma\left(\Pi_S\,(p^*, e^*, v, q)\right) = \int \Pi_S(p^*, e^*, v, q) f_1(\gamma) d\gamma \tag{3.21}$$

$$E\gamma\left(\Pi_S\,(p^*, e^*, v, q)\right) = E\gamma(d)(v - c - s \cdot q^{-1} - 0.5 \cdot i \cdot c \cdot q \cdot r^{-1}) \tag{3.22}$$

The first order derivation of the profit function with respect to the lot size is given in Equation (3.23) and the lot size which makes the profit function zero is given in Equation (3.24). In Equation (3.25), the optimal v value is given. The initial value v_0, which provides zero profit for the raw material supplier, is given in the Equation (3.26).

$$\frac{\partial \Pi_S\,(p^*, e^*, v, q)}{\partial q} = E\gamma\,(d) \cdot c \cdot q^2 - s \cdot \frac{i}{2} \cdot u \tag{3.23}$$

$$q^*(\gamma) = \sqrt{\frac{2 \cdot \mathrm{E}_{\gamma}(d^*) \cdot c \cdot u}{s \cdot i}} \tag{3.24}$$

$$v^*(\gamma) = Z \cdot v_0(\gamma) \tag{3.25}$$

$$v_0 = s + c \cdot q^{-1} + 0.5 \cdot i \cdot s \cdot q \cdot E_{\gamma}(d)^{-1} \cdot u^{-1} \tag{3.26}$$

3.1.2 Supplier-Stackelberg Game with Incomplete Information

In the Supplier Stackelberg game, raw material supplier is in the leading position which makes the first decision. Raw material supplier primarily decides the lot size and the selling price of the raw material in a way to to maximize his or her own profit in an environment in which product demand is not known, only the flexibility of price and environmental cost is known by the supplier. The objective function and constraints of the manufacturer based on v and q values determined by the raw material supplier are given in Equations (3.27) and (3.28).

Max Eω (Π_M (p, e, v^*, q^*)

Subject to

$$p^*(\omega) = \frac{a(\mathrm{E}_\omega(v^*) + m + n + r + o \cdot \mathrm{E}_\omega((q^*)^{-1}))}{a - b - 1} \tag{3.27}$$

$$\mathrm{e}^*(\omega) = \frac{b(\mathrm{E}_\omega(v^*) + m + n + r + o \cdot \mathrm{E}_\omega((q^*)^{-1}))}{a - b - 1} \tag{3.28}$$

$$\left(\frac{o+c}{q^2}\right) E_\gamma D(p^*, e^*) - 0.5 \cdot i \cdot s \cdot u^{-1} = 0 \tag{3.29}$$

$$\left(\frac{o+c}{q^2}\right) E_\gamma \left(\frac{\partial D(p^*,e^*)}{\partial v}\right) \left(v - s - \frac{c}{q}\right) + 0.5 \cdot i \cdot s \cdot u^{-1} = 0 \tag{3.30}$$

$$\frac{\partial D(p^*, e^*)}{\partial v} = \frac{(b-a)D(p^*, e^*)}{(v + m + n + r + o \cdot q^{-1})} \tag{3.31}$$

First order derivative of the demand function is given in Equation (3.31). After some simplification and expansion operations using Equations (3.27)−(3.31), Equations (3.32) and (3.33) are obtained. It is very difficult to solve these equations by integration method. Simpson's rule is a practical method for converting equations containing numerical integration into a non-integral structure and achieving quick results. When the Simpson’s Quadrature rule is applied to Equations (3.32) and (3.33) and are solved together, the optimal v and q values are reached.

$$\left(\frac{o+c}{q^2}\right) k \int_0^1 L^b((v+m+n+r+o\cdot q^{-1})^{b\left(1-\frac{1}{L}\right)} \left((1-L)-\frac{L}{b}\right)^{b\left(\frac{1}{L}-1\right)} f_1(b)db - 0.5\cdot i\cdot s\cdot u^{-1} = 0 \qquad (3.32)$$

$$\left(\frac{o+c}{q^2}\right)\cdot(v-s-c\cdot q^{-1})\cdot\frac{\left(1-\frac{1}{L}\right)}{v+m+n+r+o\cdot q^{-1}}\cdot k\int_0^1 b\cdot L^b((v+m+n+r+o\cdot q^{-1})^{b\left(1-\frac{1}{L}\right)}\left((1-L)-\frac{L}{b}\right)^{b\left(\frac{1}{L}-1\right)} f_1(b)db + 0.5\cdot i\cdot s\cdot u^{-1} = 0 \qquad (3.33)$$

3.2 Numerical Example

In this section, a numerical example is presented to illustrate the operation of the model. In the example, a two-stage supply chain consisting of a manufacturer and a raw material supplier where the raw material supplier is the leader, is discussed. The parameters used are given in Table 3.1. The unit of currency is Turkish Lira.

Table 3.1 Values of the parameters for the illustrative example

k	*o*	*i*	*u*	*m*	*n*	*r*	*L*	$\bar{c}$	σ_c	$\bar{s}$	σ_s	$\bar{b}$	σ_b	*Z*	*Y*	*t*
3500	40	0.1	1.01	2.5	1.3	1.5	0.09	200	0.5	11	0.001	0.15	0.05	1	0.2	72197

In this illustrative example, both the manufacturer and the raw material supplier know the demand coefficient *k*, ordering cost *o*, the percentage of the storage cost *i* and the production rate coefficient *u*. However, the raw material supplier does not know the exact value of the demand, only knows the *L* value which equal to the rate of elasticity coefficients. Under these conditions, the raw material supplier firstly determines the sales price of the raw material and the lot size through Equations (3.32) and (3.33). The *v* value is obtained as 97.15 and the *q* value is obtained as 12.60 by the raw material supplier. Then the manufacturer reaches 340.75 and 30.66 values for *p* and *e* respectively through the Equations (3.27) and (3.28). The greening cost is obtained as 30.40. With these values obtained, the profit function for the manufacturer becomes ₺70.38 and for the raw material supplier becomes ₺17.87. Thus, the total profit of the chain is found as ₺88.26.

3.2.1 Sensitivity Analysis

In this section, the effect of the changes in the parameters $\overline{c}$ and $\overline{b}$ on the decision variables and the profit functions are investigated. Three cases in which the standard deviation of these parameters is small, medium and large are considered. In Table 3.2, the sensitivity analysis is given for the case that the raw material suppleier does not know the $\overline{b}$ and in Table 3.3, sensitivity analysis is given for the case that the manufacturer does not know the c. It is concluded that as the standard deviations of $\overline{b}$ and $\bar{c}$ increase, p, e, g, v values also increase, while q and all the profit functions decrease.

Table 3.2 Sensitivity analysis according to σ_b

σ_b	p^*	v^*	q^*	e^*	g	Π_M	Π_S	Π_{Total}
0.01	340.75	97.15	12.60	30.66	30.40	70.38	17.87	88.26
0.02	363.20	104.07	12.42	32.68	32.42	68.07	17.82	85.90
0.05	444.02	127.98	9.16	39.96	39.70	61.61	17.42	79.04

Table 3.3 Sensitivity analysis according to σ_c

σ_c	p^*	v^*	q^*	e^*	g	Π_M	Π_S	Π_{Total}
0.5	334.17	95.13	12.63	30.07	29.81	71.10	17.88	88.98
5	334.22	95.14	12.63	30.08	29.82	71.10	17.88	88.98
50	338.61	96.47	12.51	30.47	30.21	70.63	17.87	88.51

CHAPTER FOUR
AN APPLICATION IN THE HYDRAULIC-PNEUMATIC INDUSTRY

4.1 Introduction

In the transfer of energy, systems that use liquid and gas media are called as hydraulic and pneumatic systems. In general, plastic raw materials are used extensively in the production of these systems which usually includes elements such as pumps, compressors and pipes. The unconscious usage of the plastic materials are known to be one of the major causes of environmental pollution. With the increase in environmental awareness, recycling of plastic material becomes a current issue. Governments form a number of regulations to minimize environmental pollution and businesses are expected to comply with these rules. Since the plastic is known to be the one of the most discontinued or burned material in the nature and this is a great danger to the environment, the sanctions of the governments on this issue are considerably disincentive.

In this section, the optimal raw material sales price, the product sales price, the lot size and the environmental cost of a plastic plug with a single raw material, are aimed to be found using the Stackelberg game which is a hierarchical game theoretical method. Then, experimental design method is used to investigate the effects of minor deviations on the actual parameters on the results.

The use of experimental design in the supply chain with game theoretic approaches is very limited and mostly about behavioral economics. (Katok, 2011; Katok & Pavlov, 2013). Apart from these, there are also significant studies on bargaining and market behavior between countries (Tokar, Aloysius, Waller, & Williams, 2011) and retail promotions and information sharing (Roth, Prasnikar, Okuno-Fujiwara, & Zamir, 1991) which use experimental design methodology. As a matter of fact, Loch & Wu (2008)'s paper which may be the only study dealing with Stackelberg game in the supply chain with experimental design also studies behavioral economics. Sheu (2016) applies experimental design in green supply chain.

To the best of our knowledge, this is the first study including an application of Stackelberg game approach based on asymmetric information with the environmental concerns in hydraulic-pneumatic industry. This study is also known to be the first to use Stackelberg game and full factorial experimental design methodologies in the green supply chain.

The overall procedure of proposed methodology is given at Figure 4.1.

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procedure: Proposed methodology
input: Manufacturer's financial data (*Sales revenue, Purchasing cost, Manufacturing 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: the optimal solution (price of the product, lot size, profit functions, raw material sales price, profits)
begin

//Raw material supplier's decision
determine *v, q*
//Manufacturer's decision
determine *p, e*
calculate *g*
if g > t
t=g
calculate profit functions

// Experimental design
determine factors *c,s,b*
estimate *v, q, p, e, g,* profit functions
output the maximum profit of the chain
end

Figure 4.1 The procedure of proposed methodology

4.2 Case Study

In this chapter, a Stackelberg game theory approach between the raw material supplier and the manufacturer of the plastic plug operating in the hydraulic-pneumatic industry, is considered. The manufacturer which is one of the prominent producer of the hydraulic-pneumatic components in İzmir, Turkey supplies the plastic raw material in a granular form, process and sells it directly to the end user. The company adapts the recycling system and uses it to recycle plastics, which are production wastes. The selling price of the product is determined by the manufacturer by considering the costs and the demand. The demand is determined based on the price of the product and environmental and marketing costs since these three criteria are considered to be effective in purchasing decisions of consumers.

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. Due to the importance of plastic in environmental pollution, a plastic product is selected in this study.

Manufacurers are expected to comply with the environmental rules determined by laws and international agreements, otherwise they are penalized. In the communiqué on the administrative fines to be issued in accordance with the environmental law, it is stated that the wastes left to the ground will be punished with ₺72197. (Communiqué on administrative fines to be issued pursuant to the environmental law numbered 2872, 2019).

4.3 Numerical Analysis

In this section, the relationship between a manufacturer operating in the hydraulic-pneumatic industry and a plastic raw material provider is examined for the navy conical plug, which is a special product who has single raw material. Firstly, v, q, p and e values which make maximum profit for the the raw material supplier and the manufacturer are reached. Then, with the experimental design approach, the effects of the some changes of the parameters on the v, q, p, e, g values and the profit functions are observed. Since sensitivity analysis cannot be applied in discrete systems, experimental design is chosen as the analysis method. The current situation is examined using Matlab R2018b and the experimental design is performed using the Minitab 14.

4.3.1 Current Situation

The total expenses were provided from the manufacturer on a monthly basis. These expenses are obtained by dividing the production time and multiplying by the cycle time and dividing the number of products produced. The actual parameters of the navy conical plug are given in Table 4.1.

Table 4.1 Parameters for current situation

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

The results obtained are given in Table 4.2. From the table, it is understood that 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 omiting the environmental marketing cost from the total environmental cost is 0.2111. Considering these costs, the profit of the raw material supplier is found ₺269.134, while the manufacturer 's profit is ₺403.136. It is noteworthy that the follower's profit is higher than the leader’s who is the raw material supplier. Followers can be more advantageous in the Stackelberg game due to reasons such as the amount of production or the technological infrastructure of the company. This is an example of this situation.

Table 4.2 Results

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

4.3.2 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 manufacturer, and the total profit. The supplier's setup cost and production cost and the greening / demand coefficient, which is unknown to the supplier are determined as the factors. The reason for the selection of these factors is that these factors are not exactly known by players and have the power to affect all the results. The values of these factors at each level are given in Table 4.3. In table 4.4, the full factorial experimental design with 3 factors and 3 levels and 3^3 treatment conditions are given.

Table 4.3 Values for the 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 4.4 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

The design of full factorial experiments is primarily made for the raw material sales price. Estimated effects and regression coefficients are given in Table 4.5. The adjusted determination coefficient (R-sq) demonstrates that the factors explain the result in which proportion. Therefore, the larger the adjusted determination coefficient between zero and one, the better. It is understood that the adjusted determination coefficient is acceptable for v from the Table 4.5. In addition, it is seen that only the $\bar{s}$ factor is significant. In Table 4.6, 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.

Table 4.5 Estimated effects and coefficients for 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 4.6 Analysis of variance for 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				

Figure 4.2 shows the main effects and the interactions for v. The figure shows that the factor that affects the raw material sales price most strongly is $\bar{s}$ followed by $\bar{c}$ and $\bar{b}$ respectively. As the $\bar{s}$, and $\bar{c}$ values increase, the mean v value also increases unlike the $\bar{b}$ value. In addition, since the lines in the graph intercept each other, it can be

concluded that the interaction between $\bar{c}$ and $\bar{s}$ and between $\bar{c}$ and $\bar{b}$ exists. However, it is concluded that these relationships are statistically insignificant in Table 4.5.

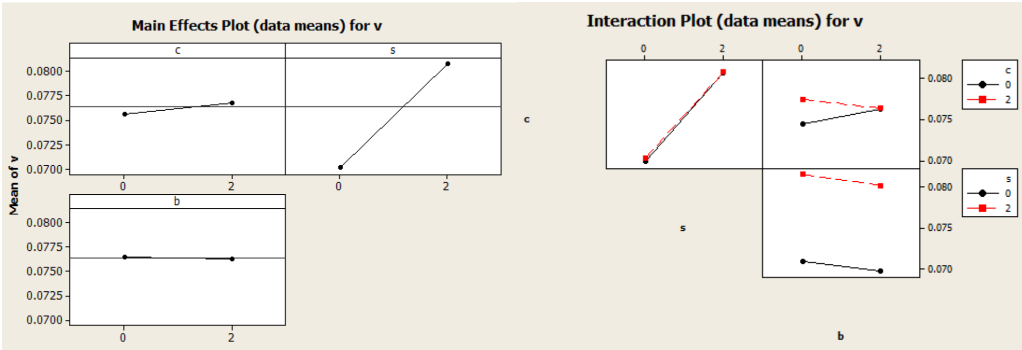

Figure 4.2 Main effects and the interactions plot for raw material sales price

In Figure 4.3 cube plot for *v* is given. For all factors and their levels, the *v* values are shown. The highest *v* value is obtained at level 2 of all factors while the lowest value is obtained at level 0 of all factors.

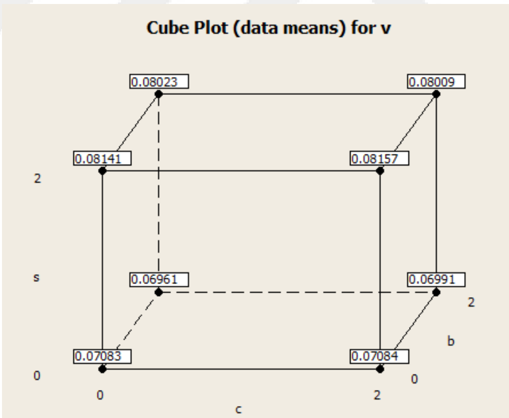

Figure 4.3 Cube plot for raw material sales price

Table 4.7 shows that no factors and interactions are statistically significant except the $\bar{s}$ factor for lot size. Moreover, since the adjusted determination coefficient is near-one, it is concluded that these factors can explain the lot size value properly. Table 4.8 concludes that only the main effects are statistically significant together.

Table 4.7 Estimated effects and coefficients for lot size

Term	**Effect**	**Coef**	**SE Coef**	**T**	**P**
Constant		117.35	1.22	96.19	0.000
c	5.74	2.87	1.494	1.92	0.07
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 4.8 Analysis of variance for 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				

Figure 4.4 shows that the factor with the strongest effect on q is $\bar{s}$ followed by $\bar{c}$ and $\bar{b}$ respectively. While $\bar{s}$ and $\bar{c}$ have positive effect on q, $\bar{b}$ has negative effect. Besides, it appears that there is only interaction between the factors $\bar{b}$ and $\bar{c}$. However, this interaction is not statistically significant. In Figure 4.5 cube plot for lot size is given. For all factors and their all levels, the q values are shown.

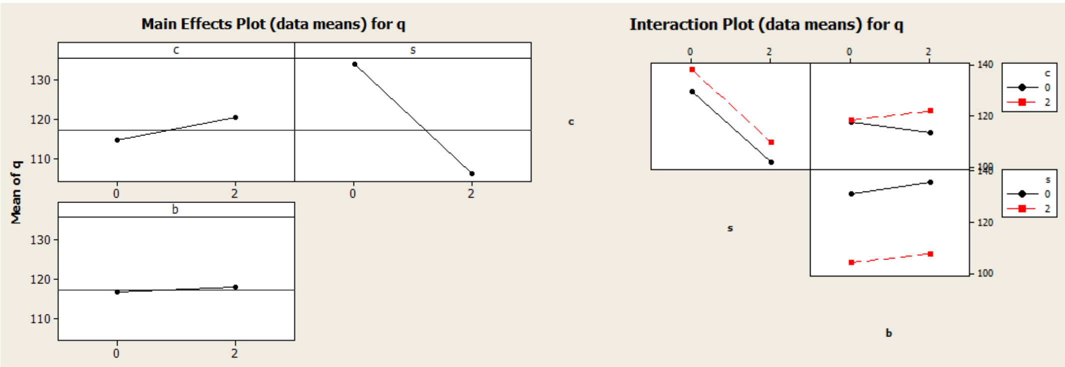

Figure 4.4 Main effects and interactions plot for lot size

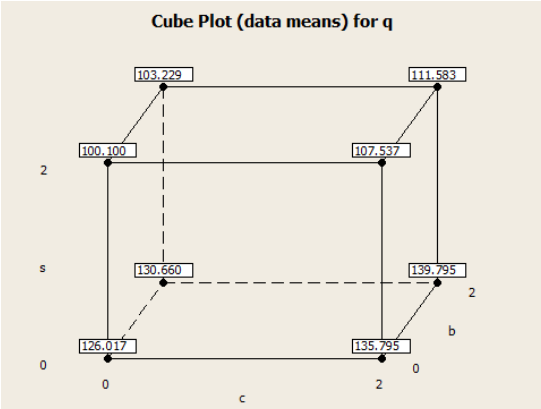

Figure 4.5 Cube plot for lot size

Table 4.9 illustrates that only $\bar{s}$ factor is statistically significant among the all factors and the interactions. The adjusted determination coefficient is high. Therefore, it is concluded that these factors can explain the *p* value properly. In Table 4.10, it is clearly seen that only the main effects are statistically significant together unlike bileteral and triple interactions.

Figure 4.6 shows that the factor with the strongest effect on *p* is *s* followed by $\bar{b}$ and $\bar{c}$ respectively. While $\bar{s}$ and $\bar{c}$ have positive effect on *p*, $\bar{b}$ has negative effect. Beside, it appears that there are interactions between the factors $\bar{b}$ and $\bar{c}$, and $\bar{s}$ and $\bar{c}$. However, these interactions are not statistically significant. In Figure 4.7 cube plot for for the product price is given. For all factors and their all levels, the *p* values are shown.

Table 4.9 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 4.10 Analysis of variance 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				

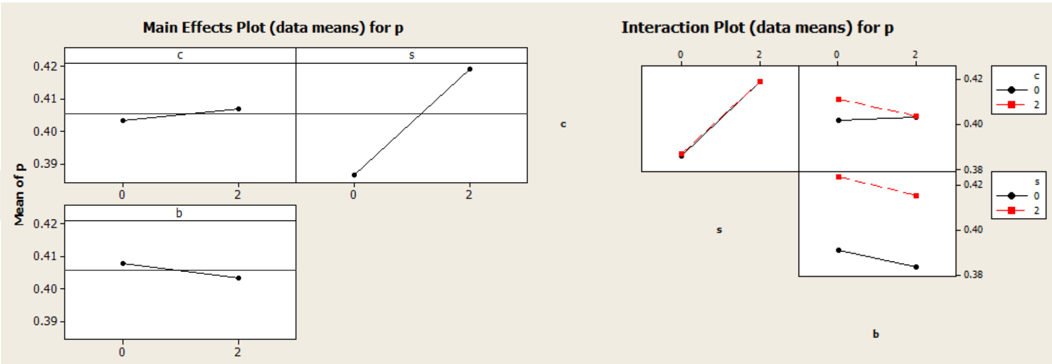

Figure 4.6 Main effects and interactions plot for the product price

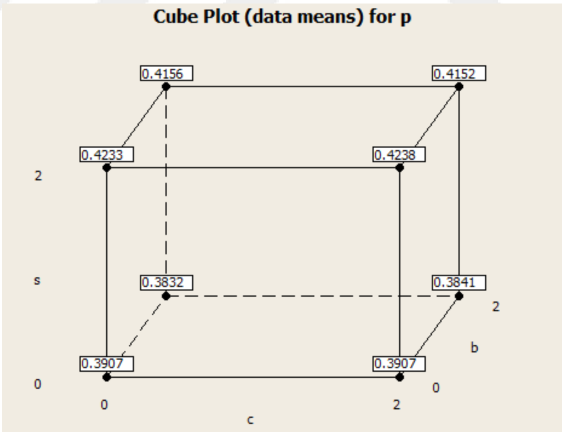

Figure 4.7 Cube plot for the product price

From Table 4.11, it is concluded that the adjusted determination coefficient is acceptable for the environmental cost. In addition, it is seen that only the $\bar{s}$ factor is significant. ANOVA table for the environmental cost is given in Table 4.12. It is seen that bilateral and triple interactions are not significant, only the main interactions are statistically significant.

Table 4.11 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 4.12 Analysis of variance for the environmental cost

Source	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				

Figure 4.8 shows that the factor with the strongest effect on e is $\bar{s}$ followed by $\bar{b}$ and $\bar{c}$, respectively. While $\bar{s}$ and $\bar{c}$ have positive effect on e, $\bar{b}$ has negative effect. Furthermore, it is obvious that there are interactions between the factors $\bar{b}$ and $\bar{c}$, and $\bar{s}$ and $\bar{c}$. However, these interactions are not statistically significant. In Figure 4.9 cube plot for e is given. For all factors and their all levels, the e values are shown.

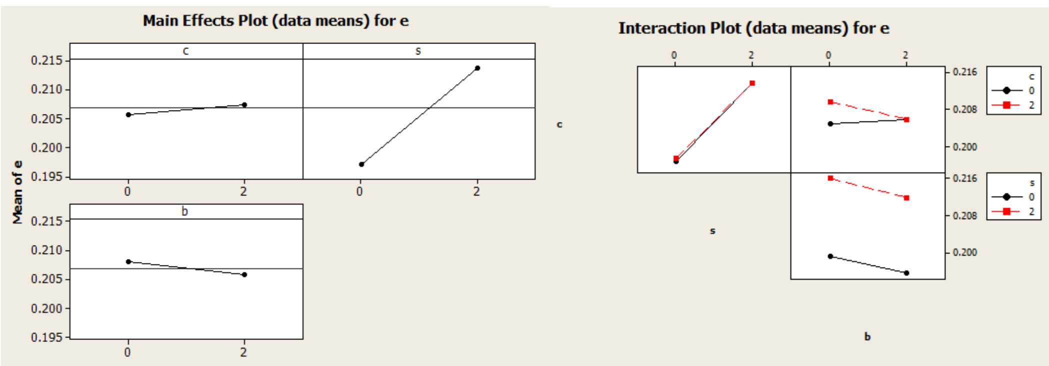

Figure 4.8 Main effects and interactions plot for the environmental cost

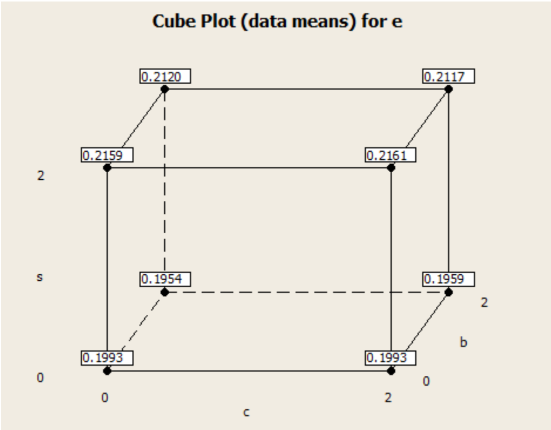

Figure 4.9 Cube plot for the environmental cost

Table 4.13 shows that no factors and interactions are statistically significant except the $\bar{s}$ factor for the greening cost. Moreover, since the adjusted determination coefficient is high, it is concluded that these factors can explain the the greening cost value thoroughly. It is understood from Table 4.14 that only the main effects are statistically significant for *g*.

Table 4.13 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 4.14 Analysis of variance 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				

Figure 4.10 shows that the factor with the strongest effect on g is $\bar{s}$ followed by $\bar{b}$ and $\bar{c}$, respectively. While $\bar{s}$ and $\bar{c}$ have positive effect on g, $\bar{b}$ has negative effect. Besides, it is seen that there are interactions between the factors $\bar{b}$ and $\bar{c}$, and $\bar{s}$ and $\bar{c}$. However, these interactions are not statistically significant. In Figure 4.11 cube plot for g is given. For all factors and their all levels, the g values are shown.

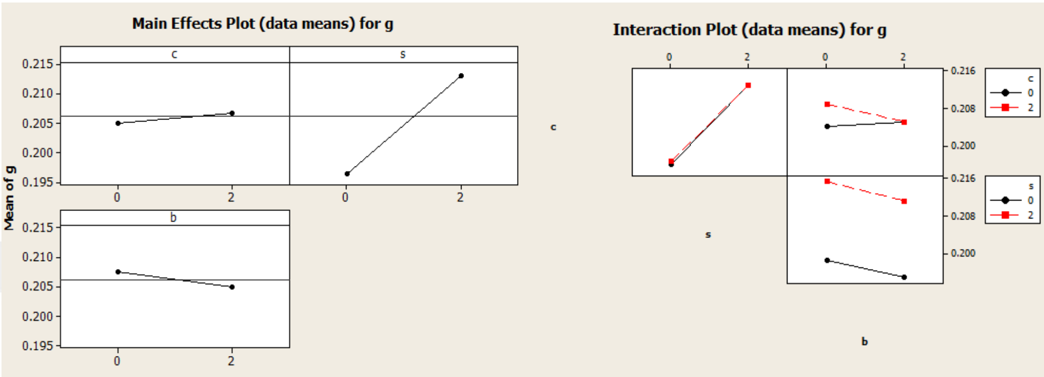

Figure 4.10 Main effects and interactions plot for the greening cost

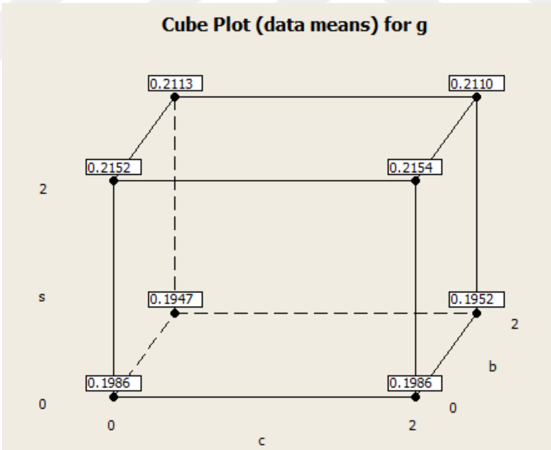

Figure 4.11 Cube plot for the greening cost

From Table 4.15, it is determined 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 $\bar{s}$ factor is significant as obtained in the previous results. ANOVA results for supplier's profit are given in Table

4.16. It is seen that bilateral and triple interactions are not significant, while only the main interactions are statistically significant.

Table 4.15 Estimated effects and coefficients for 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 4.16 Analysis of variance for 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				

Figure 4.12 shows that the factor with the strongest effect on supplier's profit is $\bar{s}$ followed by $\bar{c}$ and $\bar{b}$, respectively. While $\bar{b}$ and $\bar{c}$ have positive effect on p, $\bar{s}$ has negative effect. Furthermore, it is seen that there are interactions between the factors $\bar{b}$ and $\bar{c}$, and $\bar{s}$ and $\bar{c}$. However, these interactions are not statistically significant. In Figure 4.13 cube plot for supplier's profit is given. For all factors and their all levels, the values of supplier's profit function are shown.

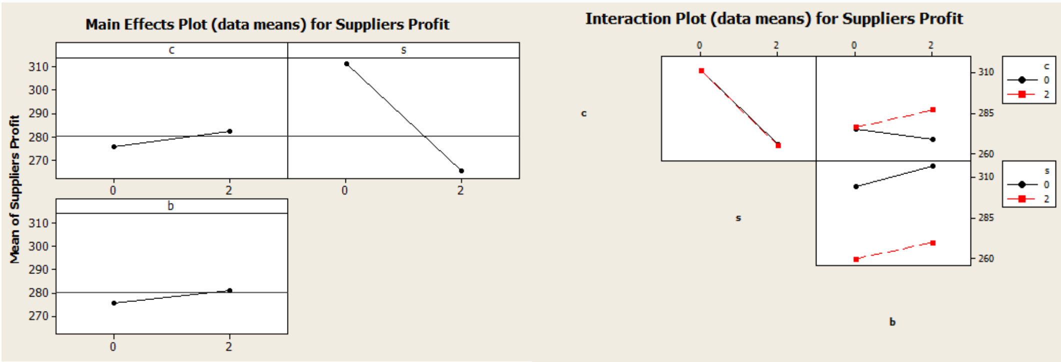

Figure 4.12 Main effects and interactions plot for supplier’s profit

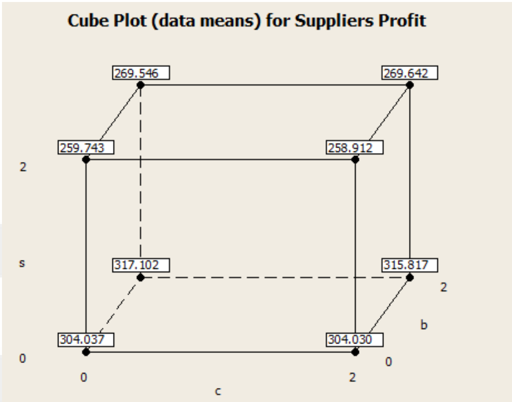

Figure 4.13 Cube plot for supplier's profit

Table 4.17 shows that no factors and interactions are statistically significant except the *s* factor for manufacturer’s profit. Moreover, since the adjusted determination coefficient is high, it is concluded that these factors can explain the manufacturer’s profit function thoroughly. It is understood that only the main effects are statistically significant from the Table 4.18 for manufacturer’s profit.

Table 4.17 Estimated effects and coefficients for manufacturer’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 4.18 Analysis of variance for manufacturer’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				

Figure 4.14 illustrates that the factor with the strongest effect on manufacturer’s profit is $\bar{s}$ followed by $\bar{b}$ and $\bar{c}$ respectively. While $\bar{s}$ and $\bar{c}$ have negative effect on manufacturer’s profit, $\bar{b}$ has positive effect. Moreover, it appears that there is only interaction between the factors $\bar{s}$ and $\bar{c}$. However, this interaction is not statistically significant. In Figure 4.15, cube plot for manufacturer’s profit is given. For all factors and their all levels, the manufacturer’s profit function values are shown.

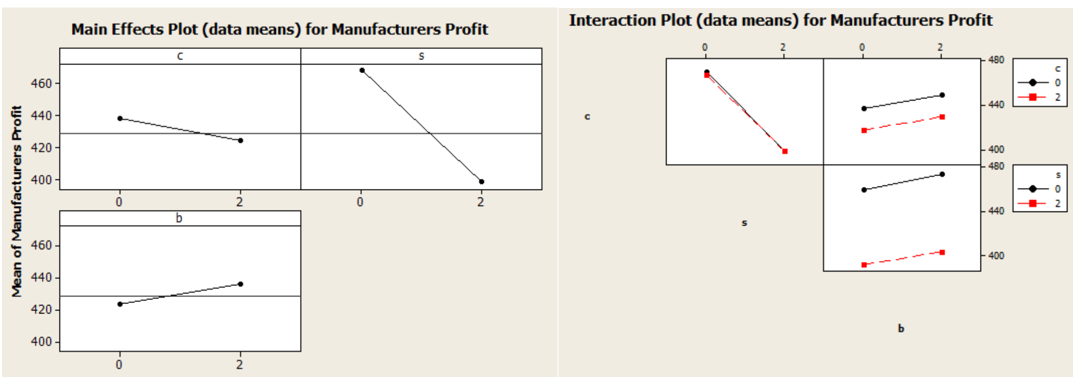

Figure 4.14 Main effects and interactions plot for manufacturer’s profit

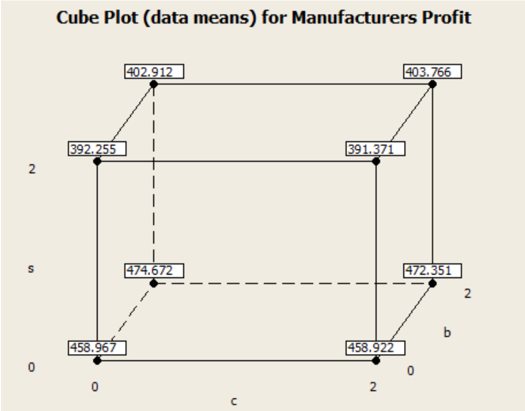

Figure 4.15 Cube plot for manufacturer's profit

From Table 4.19, it is observed that the adjusted determination coefficient is considerably high for the total profit of the chain. In addition, it is seen that only the *s* factor is significant which is similar to all of the previous results. In Table 4.20, ANOVA results are given for Total Profit of the chain. It is seen that bilateral and triple interactions are not significant, while only the main interactions are statistically significant.

Table 4.19 Estimated effects and coefficients for 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 4.20 Analysis of variance for 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				

Figure 4.16 illustrates that the factor with the strongest effect on total profit of the chain is $\bar{s}$ followed by $\bar{b}$ and $\bar{c}$ respectively. While $\bar{s}$ and $\bar{c}$ have negative effect on p, $\bar{b}$ has positive effect. Furthermore, it is seen that there are interactions between the factors $\bar{b}$ and $\bar{c}$, and $\bar{s}$ and $\bar{c}$. However, these interactions are not statistically significant. In Figure 4.17 cube plot for total profit is given. For all factors and their all levels, the values of supplier's profit function are shown. When the factor values $\bar{s}$ and $\bar{c}$ are 0, and $\bar{b}$ is 2, the maximum value of the total profit is reached.

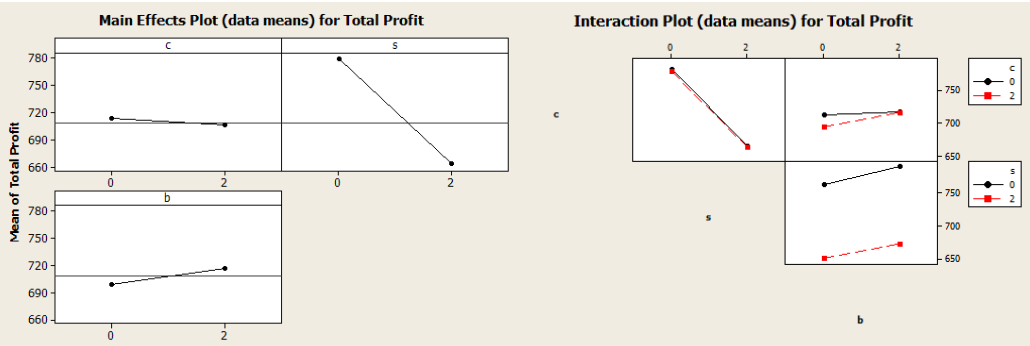

Figure 4.16 Main effects and interactions plot for total profit

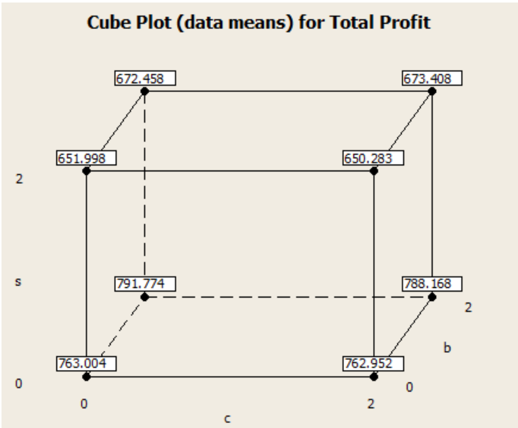

Figure 4.17 Cube plot for total profit

CHAPTER FIVE
CONCLUSION

In this thesis, a game theoretical framework is developed to analyze a green two-stage supply chain. Unlike most studies in the literature, the aim of the game is not to achieve the optimum marketing cost, rather to find the optimal value of the total greening costs, including the green marketing cost.

This game is developed based on asymmetric information. In the asymmetric information case, the players of the game are not fully aware of the other players' information. Most firms refuse to share their own costs and operational information with other companies in the chain for reasons based on competition. For this reason, the incomplete information models are more suitable for today's supply chains, but have some obstacles compared to the fully informed models in practice. For example, as the uncertain information increases, the complexity of the model also increases. In addition, the player decides in the direction of the guesses of the other players within certain deviations. This means more uncertain results are reached in comparison with the fully informed model.

In the study, a Stackelberg game approach has been developed between a manufacturer in hydraulic-pneumatic industry and a raw material supplier in a green supply chain to maximize their profit functions. The Stackelberg game model has a leader and follower. First, the leader makes the first decision, then the follower makes his decision in accordance with the leader's decision. The raw material supplier is the leader in this model and determines the sales price of the raw material and the lot size. The manufacturer is the follower and under these conditions decides the selling price of the product and the environmental cost that can be burdened. Therefore, considering the raw material cost and lot size, the optimal selling price of the product, environmental cost for one product and the optimal cost to be allocated for green marketing are obtained. These costs may be taken into consideration in new green investment decisions and advertising expenditures to be made by the company. The supplier does not know the the greenig and price elasticity coefficients of the demand of the product whereas the manufacturer does not know the costs of the supplier such as setup and production costs.

Lastly, full factorial experimental design consists of 3 factors and 3 levels is constructed and changes are observed on product and raw material sales prices, environmental cost, lot size and profit functions. It was found that the maximum total profit of the chain is at the point where the raw material supplier's the least setup and production costs and the highest greening / demand coefficient.

To the best of our knowledge, this study is the first game theoretic approach in the hydraulic-pneumatic industry. Also, as far as is known, this is the first study which compounds the Stackelberg game approach with asymmetric information and environmental concerns. This study differs from other studies in the literature by using full factorial experimental design with the Stackelberg game in green supply chain.

In future studies, a system closer to today's supply chains can be modeled by incorporating more elements such as retailers and end customers in the supply chain. Also, more suppliers can be added to the chain by selecting a complex product with more than one raw material. Different cooperative schemes can be developed and results can be compared. Also, it can be transformed into a repetitive game in which players can update their strategies according to the developing situations.

REFERENCES

Apt, K. R., & Witzel, A. (2009). A generic approach to coalition formation. *International Game Theory Review*, *11*(03), 347-367.

Athey, S., & Bagwell, K. (2001). Optimal collusion with private information. *RAND Journal of Economics*, 428-465.

Athey, S., & Bagwell, K. (2008). Collusion with persistent cost shocks. *Econometrica*, *76*(3), 493-540.

Aumann, R. (1959). Acceptable points in general cooperative n-person games. *Contributions to the Theory of Games (AM-40)*, *4*, 287-324.

Aumann, R. J. (1961). The core of a cooperative game without side payments. *Transactions of the American Mathematical Society*, *98*(3), 539-552.

Ayers, J. B. (Ed.). (2001). *Making supply chain management work: Design, implementation, partnerships, technology, and profits*. Florida: CRC Press.

Babu, S., & Mohan, U. (2018). An integrated approach to evaluating sustainability in supply chains using evolutionary game theory. *Computers & Operations Research*, *89*, 269-283.

Bai, C., & Sarkis, J. (2016). Supplier development investment strategies: a game theoretic evaluation. *Annals of Operations Research*, *240*(2), 583-615.

Barari, S., Agarwal, G., Zhang, W. C., Mahanty, B., & Tiwari, M. K. (2012). A decision framework for the analysis of green supply chain contracts: An evolutionary game approach. *Expert systems with applications*, *39*(3), 2965-2976.

Başar, T., & Olsder, G. J. (1982). *Dynamic noncooperative game theory* (2nd ed.). New York: Academic Press.

Baykasoğlu, A., & Özbel, B. K. (2016, December). Multiple Traveling Salesman Game for Cost Allocation: A Case Problem For School Bus Services. In *Lm-Scm 2016 Xıv. Internatıonal Logistics And Supply Chain Congress* (64).

Bernard, A., Haurie, A., Vielle, M., & Viguier, L. (2008). A two-level dynamic game of carbon emission trading between Russia, China, and Annex B countries. *Journal of Economic Dynamics and Control*, *32*(6), 1830-1856.

Bertrand, J. (1883), Theorie mathematique de la richesse sociale. *Journal des Savants*, 499-508.

Brunner, N., & Starkl, M. (2004). Decision aid systems for evaluating sustainability: a critical survey. *Environmental Impact Assessment Review*, *24*(4), 441-469.

Cachon, G. P., & Netessine, S. (2006). Game theory in supply chain analysis. In *TutORials in Operations Research.* (200-233). Maryland: Informs.

Callen, J. L. (1978). Financial cost allocations: A game-theoretic approach. *Accounting Review*, 53(2), 303-308.

Cao, J., Zhang, X., & Zhou, G. (2016). Supply chain coordination with revenue-sharing contracts considering carbon emissions and governmental policy making. *Environmental Progress & Sustainable Energy*, *35*(2), 479-488.

Cardaliaguet, P. (2007). Differential games with asymmetric information. *SIAM Journal on Control and Optimization*, *46*(3), 816-838.

Cardaliaguet, P., & Rainer, C. (2009). Stochastic differential games with asymmetric information. *Applied Mathematics and Optimization*, *59*(1), 1-36.

Chacko, G. K. (1961). Bargaining strategy in a production and distribution problem. *Operations Research*, *9*(6), 811-827.

Chen, Y., Liang, L., & Yang, F. (2006). A DEA game model approach to supply chain efficiency. *Annals of Operations Research*, *145*(1), 5-13.

Clemhout, S., & Wan, H. (1991). Environmental problem as a commonproperty resource game. In *Lecture Notes in Control and Information Sciences* (157th ed.) (132-154). Heidelberg: Springer Berlin.

Communiqué on administrative fines to be issued pursuant to the environmental law numbered 2872 (2019). Resmi Gazete, December 31, 2018, http://www.mevzuat.gov.tr/Metin.Aspx?MevzuatKod=9.5.31191&MevzuatIliski=0&sourceXmlSearch=%C3%A7evre

Cooper, M. C., & Ellram, L. M. (1993). Characteristics of supply chain management and the implications for purchasing and logistics strategy. *The International Journal of Logistics Management*, *4*(2), 13-24.

Cooper, M. C., Lambert, D. M., & Pagh, J. D. (1997). Supply chain management: more than a new name for logistics. *The International Journal of Logistics Management*, *8*(1), 1-14.

Cournot, A. A. (1838). *Recherches sur les principes mathématiques de la théorie des richesses par Augustin Cournot*. Paris: chez L. Hachette.

Dixit, A., Skeath, S., & Reiley, D. (2009). *Games of strategy*. New York: W. W.

Dockner, E. J., & Van Long, N. (1993). International pollution control: cooperative versus noncooperative strategies. *Journal of Environmental Economics and Management*, *25*(1), 13-29.

Dong, J., Zhang, D., & Nagurney, A. (2004). A supply chain network equilibrium model with random demands. *European Journal of Operational Research*, *156*(1), 194-212.

Du, S., Ma, F., Fu, Z., Zhu, L., & Zhang, J. (2015). Game-theoretic analysis for an emission-dependent supply chain in a 'cap-and-trade'system. *Annals of Operations Research*, *228*(1), 135-149.

Emir, Ö. (2014). *Horizontal cooperation among textile subcontractors.* Master's Thesis, Dokuz Eylül University, İzmir.

Ertogral, K., & Wu, S. D. (2001*). A bargaining game for supply chain contracting*. Retrieved June 19, 2019 from https://www.researchgate.net/profile/Kadir_Ertogral/publication/251423659_A_Bargaining_Game_for_Supply_Chain_Contracting/links/5613b56b08aea962a77fdcb2/A-Bargaining-Game-for-Supply-Chain-Contracting.pdf

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.

Esmaeili, M., Aryanezhad, M. B., & Zeephongsekul, P. (2009). A game theory approach in seller–buyer supply chain. *European Journal of Operational Research*, *195*(2), 442-448.

Fershtman, C., & Pakes, A. (2012). Dynamic games with asymmetric information: A framework for empirical work. *The Quarterly Journal of Economics*, *127*(4), 1611-1661.

Granot, D., & Sošić, G. (2003). A three-stage model for a decentralized distribution system of retailers. *Operations Research*, *51*(5), 771-784.

Greenberg, J. (1994). Coalition structures. *Handbook of Game Theory with Economic Applications*, *2*, 1305-1337.

Hamlen, S. S., Hamlen Jr, W. A., & Tschirhart, J. (1980). The use of the generalized Shapley allocation in joint cost allocation. *Accounting Review*, *55*(2), 269-287.

Hamlen, S. S., Hamlen Jr, W. A., & Tschirhart, J. T. (1977). The use of core theory in evaluating joint cost allocation schemes. *Accounting Review*, 52(3), 616-627.

Hong, Z., Chu, C., Zhang, L. L., & Yu, Y. (2017). Optimizing an emission trading scheme for local governments: A Stackelberg game model and hybrid algorithm. *International Journal of Production Economics*, *193*, 172-182.

Huang, Y., Wang, K., Zhang, T., & Pang, C. (2016). Green supply chain coordination with greenhouse gases emissions management: a game-theoretic approach. *Journal of Cleaner Production*, *112*, 2004-2014.

Hugos, M. H. (2002). *Essentials of supply chain management*. New Jersey: John Wiley & Sons.

Hurwicz, L. (1945). The theory of economic behavior. *The American Economic Review*, *35*(5), 909-925.

Kagel, J. H., Kim, C., & Moser, D. (1996). Fairness in ultimatum games with asymmetric information and asymmetric payoffs. *Games and Economic Behavior*, *13*(1), 100-110.

Kaitala, V. (1986). Game theory models of fisheries management—a survey. In *Dynamic games and applications in economics* (252-266). Berlin: Springer Heidelberg.

Katok, E. (2011). Using laboratory experiments to build better operations management models. Foundations and Trends®, *Technology, Information and Operations Management*, *5*(1), 1-86.

Katok, E., & Pavlov, V. (2013). Fairness in supply chain contracts: A laboratory study. *Journal of Operations Management*, 31(3), 129-137.

Kemahlioglu Ziya, E. (2004). *Formal methods of value sharing in supply chains*. Doctoral dissertation, Georgia Institute of Technology, Atlanta.

Kohli, R., & Park, H. (1989). A cooperative game theory model of quantity discounts. *Management Science*, *35*(6), 693-707.

Krajewska, M. A., Kopfer, H., Laporte, G., Ropke, S., & Zaccour, G. (2008). Horizontal cooperation among freight carriers: request allocation and profit sharing. *Journal of the Operational Research Society*, *59*(11), 1483-1491.

Leng, M., & Parlar, M. (2005). Game theoretic applications in supply chain management: a review. *INFOR: Information Systems and Operational Research*, *43*(3), 187-220.

Leng, M., & Parlar, M. (2009). Allocation of cost savings in a three-level supply chain with demand information sharing: A cooperative-game approach. *Operations Research*, 57(1), 200-213.

Leng, M., & Parlar, M. (2010). Game-theoretic analyses of decentralized assembly supply chains: Non-cooperative equilibria vs. coordination with cost-sharing contracts. *European Journal of Operational Research*, *204*(1), 96-104.

Levhari, D., & Mirman, L. J. (1980). The great fish war: an example using a dynamic Cournot-Nash solution. *The Bell Journal of Economics*, 322-334.

Li, S. X., Huang, Z., Zhu, J., & Chau, P. Y. (2002). Cooperative advertising, game theory and manufacturer–retailer supply chains. *Omega*, *30*(5), 347-357.

Liang, L., Yang, F., Cook, W. D., & Zhu, J. (2006). DEA models for supply chain efficiency evaluation. *Annals of Operations Research*, *145*(1), 35-49.

Lin, C. C., & Hsieh, C. C. (2012). A cooperative coalitional game in duopolistic supply-chain competition. *Networks and Spatial Economics*, *12*(1), 129-146.

Loch, C. H., & Wu, Y. (2008). Social preferences and supply chain performance: An experimental study. *Management Science*, *54*(11), 1835-1849.

Lovejoy, W. S. (2010). Bargaining chains. *Management Science*, *56*(12), 2282-2301.

Madani, S. R., & Rasti-Barzoki, M. (2017). Sustainable supply chain management with pricing, greening and governmental tariffs determining strategies: A game-theoretic approach. *Computers & Industrial Engineering*, *105*, 287-298.

Majumder, P., & Groenevelt, H. (2001). Competition in remanufacturing. *Production and Operations Management*, *10*(2), 125-141.

Mayberry, J. P., Nash, J. F., & Shubik, M. (1953). A comparison of treatments of a duopoly situation. *Econometrica: Journal of the Econometric Society*, 141-154.

Modak, N. M., Panda, S., & Sana, S. S. (2016). Three-echelon supply chain coordination considering duopolistic retailers with perfect quality products. *International Journal of Production Economics*, *182*, 564-578.

Moradinasab, N., Amin-Naseri, M. R., Behbahani, T. J., & Jafarzadeh, H. (2018). Competition and cooperation between supply chains in multi-objective petroleum green supply chain: A game theoretic approach. *Journal of Cleaner Production*, *170*, 818-841.

Nash Jr, J. F. (1950b). The bargaining problem. *Econometrica: Journal of the Econometric Society*, 155-162.

Nash, J. (1951). Non-cooperative games. *Annals of Mathematics*, 286-295.

Nash, J. (1953). Two-person cooperative games. *Econometrica: Journal of the Econometric Society*, 128-140.

Nash, J. F. (1950a). Equilibrium points in n-person games. *Proceedings of the National Academy of Sciences*, *36*(1), 48-49.

Oliver, R. K., & Webber, M. D. (1982). Supply-chain management: logistics catches up with strategy. *Outlook*, *5*(1), 42-47.

Pang, J. S., Sen, S., & Shanbhag, U. V. (2017). Two-stage non-cooperative games with risk-averse players. *Mathematical Programming*, *165*(1), 235-290.

Parlar, M., & Wang, Q. (1994). Discounting decisions in a supplier-buyer relationship with a linear buyer's demand. *IIE Transactions*, *26*(2), 34-41.

Rapoport, A. (1973). *Two-person game theory*. Ann Arbor: University of Michigan Press.

Raynaud, J. (2014). *Valuing plastics: the business case for measuring, managing and disclosing plastic use in the consumer goods industry*. Retrieved June 19, 2019 from http://wedocs.unep.org/handle/20.500.11822/9238.

Reinhardt, G., & Dada, M. (2005). Allocating the gains from resource pooling with the Shapley value. *Journal of the Operational Research Society*, *56*(8), 997-1000.

Ren, Z. J., Cohen, M. A., Ho, T. H., & Terwiesch, C. (2010). Information sharing in a long-term supply chain relationship: The role of customer review strategy. *Operations Research*, *58*(1), 81-93.

Reyniers, D. J., & Tapiero, C. S. (1995). The delivery and control of quality in supplier-producer contracts. *Management Science*, *41*(10), 1581-1589.

Rosenthal, E. C. (2008). A game-theoretic approach to transfer pricing in a vertically integrated supply chain. *International Journal of Production Economics*, *115*(2), 542-552.

Roth, A. E., Prasnikar, V., Okuno-Fujiwara, M., & Zamir, S. (1991). Bargaining and market behavior in Jerusalem, Ljubljana, Pittsburgh, and Tokyo: An experimental study. *The American Economic Review*, 1068-1095.

Schmeidler, D. (1973). Equilibrium points of nonatomic games. *Journal of Statistical Physics*, *7*(4), 295-300.

Shapley, L. S. (1953). Stochastic games. *Proceedings of the National Academy of Sciences*, *39*(10), 1095-1100.

Shapley, L. S., & Snow, R. N. (1950). Basic solutions of discrete games. *Contributions to the Theory of Games*, *1*, 27-35.

Sheu, J. B. (2016). Buyer behavior in quality-dominated multi-sourcing recyclable-material procurement of green supply chains. *Production and Operations Management*, *25*(3), 477-497.

Shubik, M. (1952). Information, theories of competition, and the theory of games. *Journal of Political Economy*, *60*(2), 145-150.

Shubik, M. (1962). Incentives, decentralized control, the assignment of joint costs and internal pricing. *Management Science*, *8*(3), 325-343.

Sturm, B., & Weimann, J. (2006). Experiments in environmental economics and some close relatives. *Journal of Economic Surveys*, *20*(3), 419-457.

Takahashi, M. (1964). Equilibrium points of stochastic non-cooperative n-person games. *Journal of Science of the Hiroshima University, Series AI (Mathematics)*, *28*(1), 95-99.

Tian, Y., Govindan, K., & Zhu, Q. (2014). A system dynamics model based on evolutionary game theory for green supply chain management diffusion among Chinese manufacturers. *Journal of Cleaner Production*, *80*, 96-105.

Tijs, S. H., & Driessen, T. S. (1986). Game theory and cost allocation Problems. *Management Science*, *32*(8), 1015-1028.

Tinç, H. K. (2018). *Tedarik zincirinde işbirlikçi oyun kuramı kullanılarak adil kâr paylaşımının yapılması ve enerji sektöründe uygulamalar.* Phd Thesis, İstanbul Technical University, İstanbul.

Tokar, T., Aloysius, J. A., Waller, M. A., & Williams, B. D. (2011). Retail promotions and information sharing in the supply chain: a controlled experiment. *The International Journal of Logistics Management*, *22*(1), 5-25.

Viswanathan, S., & Wang, Q. (2003). Discount pricing decisions in distribution channels with price-sensitive demand. *European Journal of Operational Research*, *149*(3), 571-587.

Von Neumann, J., & Morgenstern, O. (1944). Theory Of Games and Economic Behavior. Princeton: Princeton University Press.

von Stackelberg, H. (1934). *Marktform und Gleichgewicht*. Vienna: Julius Springer.

Wang, C., Wang, W., & Huang, R. (2017). Supply chain enterprise operations and government carbon tax decisions considering carbon emissions. *Journal of Cleaner Production*, *152*, 271-280.

Wang, Q., & Parlar, M. (1989). Static game theory models and their applications in management science. *European Journal of Operational Research*, *42*(1), 1-21.

Waters, C. D. J. (2003). *Logistics: an introduction to supply chain management*. New York: Palgrave Macmillan.

Wong, W. K., Qi, J., & Leung, S. Y. S. (2009). Coordinating supply chains with sales rebate contracts and vendor-managed inventory. *International Journal of Production Economics*, *120*(1), 151-161.

World Wildlife Fund [WWF]. (2018), *Plastik kapanından çıkış: Akdeniz'i plastik kirliliğinden kurtarmak*, Retrieved May 5, 2019, from https://d2hawiim0tjbd8.cloudfront.net/downloads/plastik_raporu_web_icin_2.pdf

Wu, C. H., Chen, C. W., & Hsieh, C. C. (2012). Competitive pricing decisions in a two-echelon supply chain with horizontal and vertical competition. *International Journal of Production Economics*, *135*(1), 265-274.

Xu, W., Yang, Z., & Wang, H. (2014, June). A Shapley value perspective on profit allocation for RFID technology alliance. In *2014 11th International Conference on Service Systems and Service Management (ICSSSM)* (pp. 1-4). IEEE.

Yu, Y., Chu, F., & Chen, H. (2009). A Stackelberg game and its improvement in a VMI system with a manufacturing vendor. *European Journal of Operational Research*, *192*(3), 929-948.

Yu, Y., Huang, G. Q., & Liang, L. (2009). Stackelberg game-theoretic model for optimizing advertising, pricing and inventory policies in vendor managed inventory (VMI) production supply chains. *Computers & Industrial Engineering*, *57*(1), 368-382.

Zhai, M., Zhang, X., Cheng, F., Zhou, X., & Su, X. (2017). A game-theoretic analysis of the government's role on the biomass supply chain construction. *International Journal of Ambient Energy*, *38*(5), 444-458.

Zhang, C. T., & Liu, L. P. (2013). Research on coordination mechanism in three-level green supply chain under non-cooperative game. *Applied Mathematical Modelling*, *37*(5), 3369-3379.

Zhang, J. (2009). Cost allocation for joint replenishment models. *Operations Research*, *57*(1), 146-156.

Zhao, R., Neighbour, G., Han, J., McGuire, M., & Deutz, P. (2012). Using game theory to describe strategy selection for environmental risk and carbon emissions reduction in the green supply chain. *Journal of Loss Prevention in the Process Industries*, *25*(6), 927-936.

Zhao, Y., Wang, S., Cheng, T. E., Yang, X., & Huang, Z. (2010). Coordination of supply chains by option contracts: A cooperative game theory approach. *European Journal of Operational Research*, *207*(2), 668-675.

Zhu, Q. H., & Dou, Y. J. (2007). Evolutionary game model between governments and core enterprises in greening supply chains. *Systems Engineering-theory & Practice*, *27*(12), 85-89.

APPENDICES

Proof of the pseudo-concavity of the manufacturer's production function

F is a differentiable function in S and x, $x^* \epsilon$ S. A function is said pseudo-concave if

$$F(x) > F(x^*) \Rightarrow \nabla F(x^*)'(x - x^*) < 0 \tag{A.1}$$

$$\Pi_M (p^*, e) \leq \Pi_M (p, e) \tag{A.2}$$

$$d_2 \ (v + m + n + r + e + \frac{o}{q} - p) \leq d_1 \ (v + m + n + r + e + \frac{o}{q} - p^*) \tag{A.3}$$

$$d_1(a-1)p^* - d_1 a(v + m + n + r + e + \frac{o}{q}) (p - p^*) < 0 \tag{A.4}$$

Ensuring the inequality conditions A.5 and A.6 is sufficient to prove that the profit function of the manufacturer is pseudo-concave.

$$p > p^* \tag{A.5}$$

$$v + m + n + r + e + \frac{o}{q} - p_i > 0 \text{ for } i=1,2. \tag{A.6}$$

If p was smaller than p *, d_2 would be greater than d_1, which contradicts to A.3. Therefore the opposite situation must be valid, which is p is greater than p^*. If the inequality (A.6) is less than 0, according to the (A.5), (A.7) would obtained. Since price and demand is inversely proportional, (A.5) leads to $d_2 < d_1$. This result leads to (A.8) which contradicts (A.3).

$$v + m + n + r + e + \frac{o}{q} - p^* \leq v + m + n + r + e + \frac{o}{q} - p \tag{A.7}$$

$$d_1 (v + m + n + r + e + \frac{o}{q} - p^* \leq \ d_2 (v + m + n + r + e + \frac{o}{q} - p) \tag{A.8}$$

In addition, since (a-1) is known to be greater than 0 and less than a, (A.4) is provided.

Matlab Codes

Simpson's Quadrature Method

The Solution of Equation (3.32)

```
syms v q L o b s c k i g m n r
L=0.51; o=0.002; b=3.12+0.05; d=3.12; k=3500; u=1.01; s=0.08; c=0.0011; i=0.1;
g=3.12-0.05; m=0.05; n=0.0033; r=0.0026;
%y f=0
y=L^g * (v + m + n + r + (o / q)) ^ (g*(1-1 / L))*((1-L)-(L / g)) ^ (g * (1 / L-1));
y
%z f=1
z=L^b * (v + m + n + r +(o / q))^(b * (1-1 / L))*((1-L)-(L / b))^(b *(1 / L-1));
z
%x f=0.15
x=L^d * (v + m + n + r + (o / q))^(d * (1-1 / L))*((1-L)-(L / d))^(d * (1 / L-1));
x
((((4 * x + y + z) / 6) *((o + c) /q^2)) * k) -(0.5* i * u^ (-1) *s)
```

The Solution of Equation (3.33)

```
syms v q L o b c s k i m n r
L=0.51; o=0.002; b=3.12+0.05; d=3.12; k=3500; u=1.01; s=0.08; c=0.0011; i=0.1;
g=3.12-0.05; m=0.05; n=0.0033; r=0.0026;
%y f=0
y=(g * L^g * (v + m + n + r +(o / q ))^(g *(1-(1/L))) * ((1-L)-(L / g))^(g * ((1 / L)-
1)));
y
%z f=1
z=(b * L^b * (v + m + n + r + (o / q))^(b * (1-(1 / L))) * ((1-L)-(L / b))^(b*((1 / L)-
1)));
z
```

```
%x f=0.5
x=(d * L^d * (v + m + n + r + (o / q))^(d * (1-(1 / L)))*((1-L)-(L / d))^(d*((1 / L)-1)));
x
(((4 * x + y + z) /6) *(v-s-(c / q)) *((o + c) /q^2) *((1-(1 / L)) / (v + m + n + r + (o / q))) *k) +(0.5 * i * u^-1 * s)
```

Finding v* and q*

```
syms v q
 %Equation 3.32
 one=str2sym('(217 * (73927142503421523112591793734450 / (2596148429267413814265248164610048 * (v + 1 / (500 * q) + 559 / 10000) ^ (1274 / 425)) + 5906772040358757732003178311049 / (7788445287802241442795744493830144 * (v + 1 / (500 * q) + 559 / 10000)^ (15043 / 5100)) + 10407018570534102918747871018325 / (15576890575604482885591488987660288 * (v + 1 / (500 * q) + 559 / 10000) ^ (15533 / 5100)))) / (20 * q^2) – 2 / 505=0');

%Equation 3.33
 two=str2sym('(10633*(11 / (10000*q) - v + 2 / 25) * (5766317115266878635081331152139 / (649037107316853453566312041152512 * (v + 1 / (500 * q) + 559 / 10000) ^ (1274 / 425)) + 18133790163901387118235583126097 / (7788445287802241442795744493830144 * (v + 1 / (500 * q) + 559 / 10000) ^ (15043 / 5100)) + 2749187405716092152095519316015 / (1298074214633706907132624082305024 * (v + 1 / (500*q) + 559 / 10000) ^ (15533 / 5100)))) / (1020 * q^2 * (v + 1 / (500 * q) + 559 / 10000)) + 2 / 505=0');
%pretty(y)
%simplify(y)
%answer.y
%answer.z
[q,v]=vpasolve(one,two)
```

Finding p* and e*

```
syms v q L o b s c k i a
L=0.51; o=0.002; d=3.08; k=3500; u=1.01;  i=0.1;
a=d/L;
q =126.0165889;
v =0.070831943;
p=(a * (v + m + n + r + (o / q))) / (a-d-1);
e=(d * (v + m + n + r + (o / q))) / (a-d-1);
p
e
```

Obtaining g and profit functions

```
clc;
clear;
syms k p a e b v m n r o q i m q L s c y g
k=3500; L=0.51;
p =    0.4156;
e =    0.212;
q =103.2292715;
v =0.080233544;
m=0.05; n=0.0033; r=0.0026;
o=0.002; i=0.1; b=3.14; a=b/L;
s=0.0351; c=0.0011; u=1.01;y=0.2;
%Suppliers
supplier= v * k * p^-a * e^b - s * k * p^-a * e^b- c * k * p^-a * e^b/ q - 0.5 * i *s * q /
u;
%Manufacturers
```

```
manufacturer = k * p^(1-a) * e^b - v * k *p^-a * e^b- m * k* p^-a * e^b - n * k * p^-a* e^b -r *k* p^-a * e^b- k * p^-a* e^(b+1)-o *k * p^-a * e^b / q- 0.5 *i * m * q ;

supplier
%format short
manufacturer
total=supplier + manufacturer;
total
%demand
%d = k * p^-a * e^b
g=e-y*n;
g
```