OPTIMIZATION OF DECENTRALIZED SUPPLY CHAIN SYSTEMS WITH INFORMATION SHARING AND UPSTREAM COMPETITION

by

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This is to certify that I have examined this copy of a master's thesis by

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to my family, friends and büyük beşiktaş çarşısı...

ABSTRACT

In this thesis, a multi-echelon decentralized supply chain is modeled and the impacts of vertical information sharing and horizontal manufacturer competition on different decision makers are exclusively analyzed. An optimization approach adopting MILP and Receding Horizon Predictive Control is used regarding information and material flows, respectively. For information sharing; profit, service and inventory levels and bullwhip effect are considered as major performance measures. These measures are analyzed and compared for different information sharing strategies. Information sharing generally provides better performance for all decision makers. But the relationships between these performance measures can not be generalized for different information sharing strategies and products. Transportation lead times of the manufacturers are the main parameters either amplifying or reducing the improvements due to information sharing.

The relationship between the manufacturers and distributor/retailer echelons is treated as a principle-agent interaction. The competition among manufacturers is based on sales price and quality level. While the former directly affects profit level and market share, the latter has impact on the profit level via market share. Results of the competition mainly depend on the relationship between sales price and quality levels among different feasible decision sets. The pricing power of the retailer echelon is analyzed by the incorporation of price and quality elasticity of consumers. Under such a setting retailer echelon is the only better performing party. Finally a specific game is formed to examine the cooperative behavior of manufacturers under asymmetric information. If applicable for an initial solution, cooperative behavior provides better performance for all manufacturers.

ÖZETÇE

Bu tezde, çok basamaklı ve merkezi olmayan bir tedarik zinciri sistemi modellenmekte ve dikey bilgi paylaşımıyla yatay rekabetin farklı karar vericiler üzerindeki etkisi birbirlerinden bağımsız olarak analiz edilmektedir. Sırasıyla bilgi ve malzeme akışlarına istinaden, karışık tam sayılı programlama ve gerileyen horizonda tahminsel kontrol metotlarının bileşimi olan bir eniyileme yaklaşımı benimsenmektedir. Bilgi paylaşımının analizinde; kâr, hizmet ve envanter seviyeleri ile kırbaç etkisi ana performans ölçütleri olarak alınmıştır. Bu performans ölçütleri, farklı bilgi paylaşımı stratejileri açısından analiz edilmekte ve karşılaştırılmaktadır. Bilgi paylaşımı genel olarak tüm karar vericiler için daha iyi performans sonuçları vermektedir. Ancak performans ölçütleri arasındaki ilişkiler için, farklı bilgi paylaşımı stratejileri ve ürünlere göre bir genelleme yapılamamaktadır. Üreticilerin nakliye zamanları, bilgi paylaşımından kaynaklanan iyileşmeleri kuvvetlendiren ya da zayıflatan başlıca parametrelerdir.

Üreticilerle dağıtıcı/perakendeci basamakları arasındaki ilişki bir müdür-memur ilişkisi olarak belirlenmiştir. Üreticiler arasındaki rekabet, satış fiyatı ve kalite seviyesi üzerinden gerçekleşmektedir. Satış fiyatı, kârı ve pazar payını doğrudan etkilerken; kalite seviyesi, kâr seviyesi üzerindeki etkisini pazar payı aracılığıyla hissettirir. Rekabetin sonuçları temelde, farklı olurlu karar kümelerindeki satış fiyatı ve kalite seviyesi arasındaki ilişkiye dayanır. Müşterinin fiyat ve kalite esnekleğinin modele dahil olmasıyla, perakendecinin fiyatlama gücü analiz edilmektedir. Böyle bir ortamda, kâr seviyesi açısından, sadece perakendeci daha iyi performans göstermektedir. Son olarak, özel bir oyun türü oluşturulmakta ve asimetrik bilgi durumunda üreticilerin müşterek davranışları incelenmektedir. Başlangıç sonucuna göre uygulanabilirliği varsa, üreticilerin müşterek davranmaları hepsi için daha iyi performans sonuçları sağlamaktadır.

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NOMENCLATURE

AR	Auto Regressive
ARIMA	Auto Regressive Integrated Moving Average
ARMA	Auto Regressive Moving Average
FDIS	Future Demand Information Sharing
HDIS	Historic Demand Information Sharing
IS	Information Sharing
IT	Information Technology
MILP	Mixed Integer Linear Programming
MPC	Model Predictive Control
NE	Nash Equilibrium
NIS	No Information Sharing
PQS	Profit Margin/Quality Scheme
RHPC	Receding Horizon Predictive Control
SE	Stackelberg Equilibrium
SL	Service Level

Chapter 1

INTRODUCTION

Most of the business entities related to the process of providing desired and tangible/intangible products to consumers, are participants of at least one chain-like structure. Due to the specialization aspect of economics, each participant in a chain-like structure converges to a role which is best for him in terms of both qualitative and quantitative performance measures (see Fawcett et al. [2007]). For the manufacturing industry, the specific structure is generally called supply chain systems or logistics networks. In this study however, supply chain systems is used for referring to the particular structure discussed above.

A typical supply chain system consists of suppliers, manufacturers, distributors, retailers and finally consumers. The system is generally organized as connected echelons that include business units grouped by their functions. The interrelations between members of different echelons or within an echelon correspond to transfer operations. These operations denote material and information flows, namely. The directions regarding both information and material flows depend on the nature of the system. Particularly for this study, both information and material flows are unidirectional. Information flow starts from the consumer echelon and continues towards upstream echelons, whereas material flow occurs in the opposite direction.

The members of supply chain systems tend to act individually trying to achieve their own objectives while ignoring other parties (Li and Wang [2007]). However, due to the chain-like form of the system, there exist both implicit and explicit interactions among chain members whether they conceive them or not. Therefore neglecting those interactions by setting individual objectives and following methods for accomplishing those objectives can make members of the chain underperform. At this point, as a philosophy, supply chain management emerges to overcome the problems that may arise from the aforementioned, myopic behavior by focusing on the interactions between the supply chain members and treating the supply chain as a whole. Details introduction to supply chain management can be found in the following sections.

1.1 Supply Chain Management

In the work of Cooper et al. [1997] supply chain management is defined as: "... an integrative philosophy to manage the total flow of a distribution channel from supplier to the ultimate user". Main objective of supply chain management is specifying the relationships between the supply chain members in order to coordinate the related operations within the system in such a way that overall costs are decreased whereas service levels are increased. For achieving this objective, a coherent and integrated structure is required. The key for obtaining this structure may be the cooperation of supply chain participants. However, even the ultimate solution to the management problem above seems to be very clear, the steps that should be taken to reach that solution is not so straightforward. There are some common and critical issues regarding supply chain systems which are actually the major subjects of supply chain management approaches. First of all, even the best course of action for dealing with supply chain problems is trying to find global solutions, the systems under consideration are most of the time decentralized (Li and Wang [2007]). There are various decision makers with conflicting objectives (Corbett [2001]). For instance, the retailers are in close interaction with consumers and due to the specific features of the industry they belong, flexibility in terms of product specifications and delivery times may be crucial for successful competition. However for most of the manufacturers, long production runs with large batch sizes are favorable for cost measures resulting in little flexibility. Therefore some sort of compromise must be settled if overall improvement of the system is of interest. Besides conflicting objectives of subsequent echelons, there may be competition within an echelon as well. An intra-echelon competition has impacts on both competing parties and the third parties doing business with them. Second, the supply chain systems have quite complex architectures with many parameters. The uncertainty regarding these parameters makes the setting even more complex. The major sources of uncertainty are production/transportation lead times, production yields and customer demand. Finally, there exists a significant asymmetry in the levels of useful information accessed and utilized by different echelons of the supply chain (Xu et al. [2001]). Being one of the major subjects analyzed throughout this study, this information problem is an important factor in overall supply chain inefficiency. The causes and potential results of the problem related to information issue as well as the measures that can be taken to overcome it, is discussed in Section 1.3.

1.2 Decentralization Level of the Supply Chain System

Consisting of connected but independent decision makers, the supply chain systems are decentralized structures by default. Substantial amount of effort is spent in order to create mechanisms making the supply chain system converge to centralized or coordinated situation by researchers and practitioners. However as stated in the previous sections, conflicting objectives of different decision makers combined with the complex form of the supply chain system makes it hard to find globally optimal solutions (Li and Wang [2007]). Level of decentralization depends on various parameters of the supply chain system such as number of echelons, number of decision makers in each echelon, motivation behind the objectives of different decision makers, product specifications, storage and transportation policies. Intuitively number of echelons and number of decision makers in each echelon are the main sources of decentralization. Other factors enlisted above act as intensifiers of decentralization rather than sources. However number of echelons and number of decision makers in each echelon also tend to magnify the severity of decentralization. This magnification can be quantified as information distortion and researches show that there exists a positive correlation between the number of echelons in the supply chain system and information distortion resulting in inefficiencies (Kaminsky et al. [2000]). On the other hand, product specifications such as substitutability, even can be associated with information distortion, act as sources of competition in the forms of among supply chain, among echelon or intra-echelon. Competition is another dimension in the context of decentralization since it requires very specific tools to analyze and it enables researchers to model quite realistic systems. Furthermore it is evident that while the developments in information technology initiated and accelerated globalization of supply chain systems, they also hardened the conditions of competition (Bradley et al. [1993]). So there is an increase in the efforts spent to analyze the effects of competition on individual players and related business units.

In this study, there are two distinct structures of supply chain systems that differ in the levels of decentralization. However these two structures are not completely different.

There are five echelons in the system. First and the last echelons, raw material suppliers and consumers, are not modeled as decision makers. Consumers are the initiators of information flow since they create and transmit demand amounts to the retailers. Suppliers respond to manufacturers by providing necessary raw materials and play a critical role in the material flow. Retailer and distributor echelons have their own decision makers responsible for the operation of whole echelon. Finally each member of the manufacturer echelon is a decision maker on his own. Overall supply chain systems exhibit different characteristics depending on product specifications. While analyzing the effects of information sharing, the products associated with each manufacturer are assumed to be not substitutable whereas for the incorporation of manufacturer competition to the system, the assumption of substitutable products is applied. An important remark to make, analyzes of information sharing and manufacturer competition is completely exclusive. The details regarding the configuration of manufacturer competition can be found in Section 4.1.

1.3 Information Discrepancy within the Supply Chain System

Core competencies of firms are the major factors that provide sustainable existence in complex business environments. In supply chain systems, functions of the participants can be considered within core competency concept and the positioning of the participants are mainly driven by their corresponding functions in the system. However due to particular positioning of different participants and decentralized nature of the system, the uniformity of accessible information for different supply chain members is disrupted. For example facing customer demand directly, retailer echelon can utilize historic sales or demand data which enables him at least making more accurate forecasts for the future periods. However the sole information accessible for the remaining echelons is the quantity in the order placed by a downstream unit. This difference in information levels leads to several problems for both individual supply chain members and entire system. In a setting where customer demand is uncertain, every member of each echelon has to make forecasts for sale, ordering, production and shipment decisions. While the echelon that is directly aware of the consumer behavior, retailer echelon i.e., can make accurate forecasts with an acceptable error level and place his orders to the immediate upstream echelon, other echelons make their forecasts relying on the data obtained from the historic orders given by the immediate downstream echelon.

Therefore the error level of forecasts increases as one moves from downstream to upstream resulting in inaccurate production, transportation and sales amounts. Eventually these inaccurate amounts lead to either excess inventory or underachieving service levels (Chen et al. [2000]). The severity of this information distortion depends on some factors. Long lead times make forecasting harder since customer demand depend on many parameters and a change in these parameters during lead time will increase forecasting error. Furthermore, significant variations in retail prices can lead retailers to build up inventory when prices are low by ordering in large amounts and when prices start to increase this time they try to diminish their inventory and consequently their order levels decline drastically. Unaware of the retail price levels, preceding echelons encounter highly variational orders resulting in inefficiencies and high costs. Finally, highly instable customer demand can lead retailers to think they may face a shortage so they give orders which are quite larger then their regular order quantities. The impact of this policy will be similar to the case related to the varying price levels (Kaminsky et al. [2000]).

A simple yet effective approach to overcome this problem is information sharing. By information sharing, lead time reduction, more accurate forecasts and better coordination of the entire supply chain system can be obtained. There are various information sharing strategies that can be applied. In this study, historic and advance demand(forecast) information sharing strategies are considered. These strategies are analyzed in detail in Section 3.2.

1.4 Objectives of the Study

In this thesis a multi-echelon supply chain system is considered in order to analyze different information sharing structures proposed for reducing the negative impacts of information distortion. The model is organized as a decentralized system consisting of multiple decision makers since the severity of information distortion is expected to be highest in such a system. Second aim is analyzing the effects of upstream competition on the system since it stands in the middle of decentralized and informed decision making. Competing manufacturers naturally make independent decisions however due to the special structure of the competition they also have access to either limited or complete information about different system parameters.

Chapter 2

LITERATURE REVIEW

In this chapter of the thesis, a review of the related literature is presented. There are three major related fields of research. First one is decentralized control of supply chain systems. As a tool for mitigating the consequences of decentralization related to information distortion, information sharing in supply chain systems is the second major element of the study. Finally, considered as an advanced level of decentralization, manufacturer (upstream) competition constitutes the third part of the thesis. Following three sections are devoted to existing literature containing the subjects stated above.

2.1 Decentralized Control of Supply Chain Systems

Supply chain systems consist of different functional units organized according to specific exogenous and endogenous factors. Each and every participant of the system operates with dynamic objectives belonging to different managerial decision levels. In management science, there exist widely accepted concepts for analyzing the relationship between the decisions made and the time horizon they are associated with. Operational decisions include short term activities such as production/transportation/sales quantities. Tactical decisions are generally made for one or two years and they may be the selection of inventory control policies or re-engineering of an existing production line. Finally, strategic decisions are long term ones spanning two or more years and they substantially affect the scopes of the former decision levels. Instances for these type of decisions may be entering a new market or merging with another company (Lambert et al. [1998]). In order to realize these decisions of any level, firms require resources. Since the availability and efficient use of these resources greatly depend on the decisions made by the related independent actors and the way they operate, improvements in the performance of a system participant can make the entire system perform better. Combining with the fact that most supply chain systems are decentralized structures by nature, it is essential to preserve the decentralization assumption while modeling supply chain systems together with designing strategies/policies for better performance. There are existing approaches for eliminating the problems emerging from decentralization. These may be aligning the objectives, incentives and risk levels of the system participants by special types of contracts and/or better use of information. The former one is not in the scope of this study and the literature related to the latter is presented in Section 2.2. In this section, existing decentralized modeling and optimization approaches are presented.

Min and Zhou [2002] presented a general discussion of the challenges in supply chain modeling and tips for successfully overcoming those challenges. Lee and Billington [1993] with a narrower scope compared with the study above, focused on decentralized supply chain systems. An existing case of Hewlett-Packard (HP) company requiring a decentralized business model was analyzed and based on the devised model, existing difficulties and opportunities in the future for better modeling were discussed.

For incorporating decentralization, multi agent simulation based approaches are also widely used. Swaminathan et al. [1998] proposed a modeling framework which is capable of handling different decision makers and relationships among them. The study also had an objective of maintaining an appropriate balance between the detail level of modeling the supply chain system and the effort required to conduct the corresponding modeling. Lin et al. [1998] used multi agent simulation in order to analyze a system proposed by them which is called Multi Agent Information System (MAIS). Under different scenario conditions in a decentralized supply chain setting, they assessed potential improvement strategies. Perea-Lopez et al. [2001] devised a framework for handling decentralized behavior of the participants of a multi-product,multi-stage distribution network and analyzing several heuristic control laws and their impacts on costs, customer satisfaction and stability of inventories. Simulation was the main tool used in the study. Carvalho and Custódio [2005] developed a comprehensive decision support tool using multi agent simulation as an alternative to classical optimization. Their aim was to design a modeling and analyzing framework for decentralized supply chains that can contain almost infinitely many agents, heuristics, multiple applicable strategies and tactics, various performance measures, deterministic and stochastic behavior. They also provide reports about the application of their proposed approach on industrial examples.

Decomposition techniques were also considered in order to account for decentralization. Andersson et al. [1998] analyzed a supply chain consisting of one central warehouse and multiple retailers. Stochastic lead times of the retailers were approximated by their averages. Consequently, the large problem could be separated into smaller,single echelon and independent ones. The information regarding the consequences of the decisions of the central warehouse on individual retailers is transmitted via the marginal cost increase due to an alteration in the expected lead time. By utilizing this information solutions close to the optimal reorder points for the centralized system were achievable. Andersson and Marklund [2000] contributed to the former study with a generalization which enables the retailers to order non-identical quantities and an alternative optimization approach with better convergence.

The main modeling and optimization technique used in this study is Model Predictive Control. Therefore it is essential to provide the existing literature regarding the applications of MPC in supply chain management. Technical details pertaining MPC can be found in Section 3.1.2. Tzafestas et al. [1997] drew upon MPC as a decision making instrument for detailed production planning problems and coping with stochastic features of the problem. Numerical experiments were conducted to analyze the flexibility and effectiveness of the proposed framework. Perea-Lopez et al. [2003] enhanced the use of MPC by applying to multi-echelon, multi-product distribution networks. They built a MILP model including the separate nodes of the system and information and material flows between the nodes. A rolling horizon approach was used in order to revise the decision variables parallel to the alterations realized in the supply chain system are realized. Furthermore, centralized and decentralized operation of the system were compared in an example. Another model of a supply chain system consisting of multiple products and echelons was built by Seferlis and Giannelos [2004]. A multi-variable MPC was applied as the optimization framework. In order to maintain stability and sufficiency of inventories in every node, a move suppression approach and dedicated controller mechanism were used. Numerical results regarding the proposed optimization approach indicated favorable dynamic performance for both deterministic and stochastic demand scenarios. Mestan et al. [2006] combined MPC with hybrid systems approach. Existence of continuous and discrete dynamics and logic rules were the sources of hybridness. The supply chain system was modeled as a Mixed Logical Dynamical

(MLD) system. Under stochastic consumer demand, centralized and different configurations of decentralized systems were analyzed and compared. A specific example of MPC application can be found in the study of Wang and Rivera [2008]. They preferred MPC in order to model a complex semiconductor industry. Main sources of complexity are related to the special features of the semiconductor industry such as long lead times, unique constraints and stochasticity in critical system parameters. Also nonlinearity is included in the formulation. However the system under consideration is a centralized one. A review study about different elaborate control methodologies besides MPC can be found in the work of Sarimveis et al. [2008]. Advantages, vulnerable points and difficulties for each methodology were discussed in the study.

Supply chain contracts have drawn significant attention from researchers and they are also widely used by industrial practitioners. These contracts work as coordination mechanisms to deal with the inefficiencies caused by decentralization. A detailed study on supply chain contracts was done by Cachon [2003] but those type of mechanisms are not included in this study.

Competition in supply chain systems can be considered as another level of decentralization but as a result of the excessive research efforts, a separate section is dedicated to the existing literature about this topic and can be found in Section 2.3.

2.2 Information Sharing in Supply Chain Systems

Developments in information technology enabled users to acquire, process and utilize information in cost efficient, flexible and effective ways. Before these developments even access to valuable information was quite troublesome for individuals and consequently organizations. The difficulties faced in obtaining and interpreting information throughout the supply chain induced inflexibility, destabilization in costs and inventories and inefficiencies due to these effects. Today, however, professionals are aware of the opportunities that can arise by appropriate use of IT. These opportunities are also being evaluated and analyzed by researchers substantially and a survey of existing literature about IS in supply chain systems is presented below.

Most of studies related to IS focuses on sharing demand information. This concentration is indeed intuitive since consumer demand can be considered as the initiator of the information flow in the supply chain systems. Chen [1998] considered a serial inventory system with two inventory policies. First policy was based on echelon stock and necessitated the centralization of demand information because the reorder points of the individual stages were calculated by taking the inventory position of all downstream stages into account as well as their own inventory position. Second policy is based on installation stock and did not require centralized demand information since each stage(installation) decided on his reorder point without considering the inventory of positions of other installations. In order to quantify the value of centralized demand information and relationship between important system parameters, comprehensive numerical work was conducted. Lee and Whang [1999] discussed properties of incentive alignment mechanisms and introduced a combination of policies that satisfies those properties; cost conservation, incentive compatibility and informational decentralizability, namely. Cachon and Fisher [2000] compared two types of opportunities emerging from information technology which are information sharing and lead time/batch size reduction. For the system parameters they use, latter yielded greater performance improvement in terms of cost. Lee et al. [2000] considered a simple two level supply chain with non-stationary customer demand. They analyzed the impact of sharing demand information on the supply chain participants and the relationship between the magnitude of the improvement and replenishment lead time, standard deviation and correlation coefficient of end demand. They concluded that improvement is greater when demand is significantly correlated. Raghunathan [2001] referred to the study by Lee et al. [2000] and showed that if the manufacturer utilized the complete historic order information to which he had readily access instead of using an AR(1) process for forecasting retailer order quantity, the benefits of investing in a cross-company demand information sharing system would be insignificant. Zhao and Simchi-Levi [2001] modeled a two stage supply chain system with a capacitated manufacturer and a retailer facing independently distributed demand. They used time dependent cost functions and analyzed the effect of information sharing on the cost and service level of the manufacturer. They also provided a new methodology to model the induced Markov chains under cyclic order-up-to policy. Moinzadeh [2002] considered a two stage supply chain system consisting of a single manufacturer and multiple retailers selling a single product. A centralized system distributing demand and inventory information among supply chain participants is compared with a decentralized installation stock policy. They determined the parameter combinations such that the improvement due to information sharing is maximum. Zhao et al. [2002] pointed out the importance of proper forecasting method selection and they concluded that suitable forecast models both improve supply chain performance and the value of information sharing. In a system consisting of a capacity constrained manufacturer and multiple retailers, they analyzed the relationship between different demand patterns faced by the retailer, capacity tightness faced by the manufacturer and the value of information sharing. A two stage supply chain containing a manufacturer and multiple retailers was examined also by Gaur et al. [2005]. Retailers faced ARMA(1,1) demand. They mainly analyzed three distinct scenarios. In the first scenario manufacturer infers demand information from orders placed by the retailers. In the second scenario retailers share demand information with the manufacturer. In the last scenario manufacturer only considers the most recent orders in his production planning. Inferring or sharing demand information resulted in a reduction in the safety stock of the manufacturer for the first and the second cases but an increase for the third case. Huang and Iravani [2005] introduced selective-information sharing concept meaning that a capacitated manufacturer obtains demand and inventory information from only one of the two retailers. For their setting, a state dependent base stock policy is optimal. They compared the relative benefits provided by each retailer and investigated the effects of various system parameters on the value of information sharing. A four tier supply chain system was analyzed by Viswanathan et al. [2006]. A synchronized replenishment system was compared with two information sharing schemes: *i.* sharing end user demand history and *ii.* sharing planned order schedule of the immediate down stream echelon. In the proposed replenishment system, the retailer chooses a fixed order interval and the upstream echelons satisfy the corresponding orders only at integer multiples of the interval determined by the retailer. Major conclusion was the potential better performance of the proposed replenishment scheme relative to the two information sharing schemes. Hsiao and Shieh [2006] focused primarily on bullwhip effect in a two echelon supply chain consisting of one supplier and one retailer. Demand faced by the retailer was modeled as a ARIMA(0,1,q) process. They concluded that increasing the value of q, moving average component, makes the bullwhip effect more significant whether information is shared or not. Furthermore bullwhip effect turned out to be greater if information is shared and if q is increased the difference between the two scenarios in terms of bullwhip effect also increases. Chen et al. [2007] analyzed eight different information sharing cases which are the subsets of the capacity;demand;inventory information set including no information sharing case. They used Data Envelopment Analysis (DEA) in order to consistently measure the effects of the different information sharing schemes on the supply chain in terms of total supply chain cost, supply chain fulfill rate, supply chain service level and supply chain order cycle time. Schmidt [2007] conducted a simulation analysis of a three stage supply chain system and concluded that information sharing can have disadvantages such as a drop in the service levels as a consequence of too much elimination of the safety stocks. Wu and Cheng [2008] considered three levels of information sharing in a three stage supply chain system. There was no information sharing in the first level. In the second level each echelon places orders by taking both the quantity placed by the immediate downstream echelon and customer demand information into account. In the last level orders of each echelon are placed relying only on customer demand information. The results indicated that as the level of information increases, inventory level and expected cost of the manufacturer and distributor echelons decrease. Chen and Lee [2009] proposed an order variability smoothing policy used by the retailer in a two level supply chain. They sought best possible smoothing parameters which are beneficial for the whole system. In addition, instead of customer demand information, information regarding the future order projections of the retailer was shared so that the supplier can determine the stochastic behavior of the ordering process for the retailer.

Obtaining advance demand information can reduce the level of uncertainty regarding customer demand significantly resulting in more accurate planning and improved performance in terms of inventory levels and customer satisfaction. Thonemann [2002] introduced two types of advance demand information (ADI) types. First one is called aggregate advance demand information (A-ADI) containing only the information regarding whether customers will place an order for some product or not. It is important to note answers to questions which product will be ordered and which manufacturer will receive the order remain uncertain. In the second scheme, detailed advance demand information (D-ADI) namely, the first question stated above is answered but the second one again remains uncertain. The unique feature of this study is incorporation of information sharing while possessing a substantial amount of uncertainty. Two distinct supply chain systems which differ in the number of products and demand rates for those products were analyzed. The conditions under which the benefits of sharing A-ADI and D-ADI were also determined.

Inventory levels are in the center of the trade off between sustainable costs and acceptable customer satisfaction. Therefore information regarding the inventory levels of the supply chain participants is quite important for the sound operation of the whole system. By knowing the inventory position of an preceding/succeeding node/echelon, better planning can be conducted for instance by adjusting order or production amounts. Studies by Moinzadeh [2002], Huang and Iravani [2005] and Chen et al. [2007] provide instrumental insight about the concept of inventory information sharing.

Gavirneni et al. [1999] analyzed three cases in a two level supply chain with one supplier and one retailer. In the first case the supplier possesses only past demand data. In the second case retailer shares all parameters defining his order up to policy and the distribution of the customer demand. In the third case additional to the information shared in the second case, the supplier also knows the inventory position of the retailer. This work distinguishes from the related literature since the shared information is a complete policy rather than a single parameter such as customer demand or inventory position of another actor.

In an interesting study by He et al. [2002], a two level continuous time production system was modeled. A warehouse provides necessary raw materials to a manufacturer and the manufacturer fulfils customer demand. The manufacturer shares his production queue length (unfulfilled demand) with the warehouse so that he can make more accurate replenishment decisions consequently providing raw materials to the manufacturer efficiently. Moreover, they show traditional base stock policies may not be appropriate to use in terms of performance if the warehouse knows the queue length fully or partially.

2.3 Competition in Supply Chain Systems

In most of the industrial relationships, price is the key element that drives the demand rationing process. According the fundamental supply-demand aspect of economics, for a given level of supply/demand, excess supply/demand is eliminated by properly adjusting the price resulting in efficient use of the limited resources. However in the case of multiple profit oriented product/service providers, rationing by price itself is not sufficient for efficient use of resources. Individual actors must plan their actions by not taking only the customer behavior into account but also potential actions regarding other parties. This planning and execution process can be named as competition and has been analyzed primarily in economics. Since free market system is widely applicable in most of the countries possessing significant industrial power, different types and levels of competition with an increasing severity due to globalization, exists in almost every single industry (see Enright [1999]). This situation has led supply chain researchers to incorporate competition into supply chain analysis.

There are mainly three levels of competition applicable for supply chain systems. Competition can be between distinct supply chain systems. In this situation, efforts belonging to integration and coordination within supply chain systems must have maximum importance. Since competition is between whole systems, operating towards the success of the whole system will probably yield better results than acting independently for achieving individual objectives. If competition exists between different echelons of the supply chain system, it is called vertical competition and can be considered as a result of conflicting objectives stated in Section 1.1, in decentralized systems . Finally there can be competition within an echelon which is called horizontal competition. In this study a special case of horizontal competition is analyzed in which manufacturers compete for supplying a product in a multi echelon supply chain system.

Existing literature related to competition in supply chain systems is organized in three groups. In the first part, previous work about belonging to vertical competition in supply chain systems is presented. Other parts contain two different types of horizontal competition; retailer (downstream) and manufacturer (upstream) competition, respectively. Most of these studies include certain assumptions and tools belonging to game theory but these aspects are presented in Section 4.2 in detail.

Cachon and Zipkin [1999] analyzed a two level supply chain system consisting of one supplier and a retailer. Retailer faced stationary stochastic demand and the transportation lead times were constant. Supplier and retailer simultaneously determine their own base stock levels minimizing their costs. Two different inventory tracking methods were used; local (installation) inventory and echelon inventory. Centralized and Nash Equilibrium solutions were compared and NE solution turned out to be less efficient. Centralized solution was obtainable by the use of transfer payments in NE solution case. Furthermore Stackelberg solutions were discussed. These vertical competition cases are investigated also in studies belonging to channel structures. The term channel structure stands for the relationship between buyers and sellers basically, hence is quite similar to the interactions in supply chain systems. In the study of Kadiyali et al. [2000], a two level channel structure was modeled and the power of each channel member was determined empirically through game theoretic approaches. The power of a channel member was considered as the ability to utilize price in order to increase the proportion of channel profits he gets. Corbett and Karmarkar [2001] examined an entry game in a multi echelon supply chain system with deterministic price sensitive customer demand. Entrants simultaneously choose production quantities (Cournot Competition) and the relationship between the number of entrants and prices and production quantities was derived. In addition vertical integration in a two echelon supply chain was analyzed. They also investigated the effect of fixed and variable cost structures on the outline of competition. Nagurney et al. [2002] considered a two level supply chain system with random customer demand. They modeled the optimization behavior of different decision makers and derived equilibrium conditions. They used finite dimensional variational inequalities in order to obtain existence and uniqueness of the equilibrium. Those inequalities were utilized also to maintain convergence for the optimization procedure introduced in the study. Lau and Lau [2005] discussed the setbacks of the existing studies in two echelon vertical gaming structures due to the assumptions of symmetric information and deterministic demand. In order to justify their point they introduced some basic insight about the incorporation of stochasticity and asymmetric information. Zhang [2006] incorporated horizontal inventory information sharing of two suppliers which are members of the downstream echelon in a two echelon supply chain system quite similar to the one in the work of Cachon and Zipkin [1999]. The effects of information sharing on the competition penalty varies in different cases. Liu et al. [2007] analyzed the Stackelberg game between a supplier and retailer facing lead time and price sensitive end demand. Manufacturer was picked to be the Stackelberg leader hence retailer made his decisions after the supplier announced his decision. The decentralized scheme turned out to be less efficient relative to centralized scheme due to the existence of double marginalization. But the significance of the inefficiency substantially depends on operational factors hence in a setting where those factors dominate the impact of decentralization can be sufficiently neutralized. Another two stage decentralized supply chain system was considered by Jemai and Karaesmen [2007]. Each echelon adapted base stock policies and simultaneously determine their policy parameter. NE solutions are explicitly identified and inefficiencies regarding those solutions were shown. Simple linear contracts designed to eliminate such efficiencies were analyzed as well as Stackelberg case.

Horizontal competition of downstream nodes constitutes a significant part in the analysis of competition in supply chain systems. There is a comprehensive study by Iyer [1998] including competing retailers and a single manufacturer. Retailers compete on various factors such as price, free repair, faster check out or after sales service. In order for the manufacturer to coordinate the competing retailers, different contract structures for different scenarios were devised. Li [2002] considered a two level supply chain containing a manufacturer and Cournot competitor retailers. Vertical demand information sharing was included and two distinct effects of this incorporation were analyzed. First effect is called direct effect and generated by the alterations in strategies made by the information sharing parties. Second effect is named as leakage effect and resulted by the changes in strategies made by the parties different from information sharing ones since they infer from the actions of the information sharing parties. It was shown that leakage effect restrains retailers from sharing their demand information rather promotes sharing cost information. On the other hand direct effect always makes the retailers not share their information. In addition, the ways that the manufacturer can facilitate the conditions to align incentives of the retailers to make them share information by means of price setting was discussed. Cachon and Lariviere [2005] showed revenue sharing contracts can coordinate (obtain total profit equal to centralized profit) a supply chain with retailers competing in Cournot competition or fixed price Newsvendor competitors. Yao et al. [2008] analyzed the revenue sharing contract offered to the competing retailers by a Stackelberg leader manufacturer. After receiving the contract parameters from the manufacturer, retailers simultaneously determine their order quantity and sales price in the classic Newsvendor setting. It was shown that revenue sharing contract can yield better performance compared to whole sale price contract.

In this last part of Section 2.3 previous work regarding horizontal competition in the upstream echelon of supply chain systems are presented. Choi [1991] analyzed different dominance schemes in a system of two manufacturers and a common retailer. There were three configurations: Manufacturer Stackelberg, retailer Stackelberg and vertical Nash (all parties decide simultaneously). According to the study, the behavior of the decision makers heavily depend on the type of the demand function. In the case of linear demand function, the retailer favors multiple manufacturer situation. However if the demand function is nonlinear, retailer favors trading with the manufacturers separately and manufacturers also favor working with exclusive dealers (separate retailers). Furthermore product differentiation also induces switching to exclusive dealer system for all of the channel members. Draganska and Klapper [2007] identified the factors related to retail environment that affect the structure of competition between manufacturers and the power of the retailer on the competing manufacturers. Such factors in the study were size of the retailer, assortment depth of the retailer and category expertise. They provide numerical reports obtained by the application of the proposed approach using data from ground coffee category from Germany and results show that parameters of the retail environment have significant impact on the intensity of upstream competition.

The main contribution of this study when compared to the existing work presented in the former sections, is the proposal of a realistic supply chain model and a comprehensive solution approach to the problems regarding decentralization and differences in level of accessible information. Utilization of MPC enables incorporating stochasticity into a complex and detailed model. However previous work that adopted MPC as the modeling and solution approach for decentralized systems neither contain elaborate information sharing strategies nor consider any kind of competition in the supply chains they present. On the other hand, most of the studies regarding information sharing and competition in the supply chain systems are analytical models limited in capturing the complex operation of a practical, multi echelon and decentralized system. Consequently, the contribution of this study can be summarized as the proposal of a realistic supply chain system and institution of a rigorous solution approach including the analysis of the effects of vertical information sharing and horizontal upstream competition.

Chapter 3

VERTICAL INFORMATION SHARING IN DECENTRALIZED SUPPLY CHAIN SYSTEMS

In this chapter, details regarding the setting, mathematical model, optimization procedure (MILP & MPC) of the supply chain system are introduced. Furthermore three information sharing schemes are presented and numerical results regarding the corresponding schemes are discussed.

3.1 Decentralized Supply Chain System

The particular supply chain system considered in this study is a five echelon decentralized one. The five echelons ordered from upstream to downstream are supplier, manufacturer, distributor, retailer and customer respectively. Supplier and customer echelons are not modeled as decision makers yet they are the initiators of material and information (demand) flows of the system. For this chapter only, there are two independent manufacturers with completely different and not substitutable products. Therefore demand for a product supplied by a manufacturer is simply obtained by dividing the total demand at a retailer node by the number of manufacturers. Product units assumed to be continuous for computational purposes. The nodes which constitute the distributor and retailer echelons are centralized within their own echelon only. However two echelons act independently from each other. Consequently, there are four decision makers: Two manufacturers and independent optimizers of distributor and retailer echelons. Each decision maker has an aim to maximize his own profit in contrast with a centralized system.

Lead times for production and transportation are considered to be fixed to non-zero values. Therefore each decision maker has to make forecasts prior to an order placed by his immediate downstream echelon. Demand faced by the retailer is random and seasonal. Manufacturer nodes have fixed and variable production costs that force them to produce in batches. Each manufacturer has a single production line and production is assumed not to be preemptive. Therefore during a production lead time another run can not be started. There is a preset quota arrangement between distributor and retailer nodes. An order quantity placed by a retailer node to a distributor node cannot exceed a specified amount. This specified amount that will be available for the use of corresponding retailer node in a particular period is determined by multiplying the total quantity in the orders that will be available for use in the same period, by the quota (percentage) stated in the arrangement. Sales price by a node is calculated by adding a fixed margin to the purchasing price paid to the upstream echelon. Since the prices are fixed, there is no need to incorporate price elasticity into the model. All nodes have inventory capacities. In addition distributor nodes and manufacturers have transportation capacities and manufacturers also have production capacities. An unsatisfied demand is assumed to be lost without any additional penalties, so backlogging is excluded. If the exact order amount of a node is less than the transportation node of the downstream node, the excess amount is salvaged by the shipping party. The optimization horizon has a fixed length. Each manufacturer has to select an information sharing scheme prior to the optimization horizon. This decision can be categorized as strategic since it has long lasting effects and cannot be altered during the optimization horizon.

The major problem in the operation of a such supply chain system introduced above is the lack of demand information for manufacturers and distributor nodes. Without sufficient information about customer demand they have to forecast relying on only the information obtained from the orders placed by their immediate downstream echelons. Especially in settings like the one in this study where customer demand is non stationary (seasonal) and lead times exist, shortages or excess inventory levels are faced with high frequency since customer demand can not be followed concurrently by all of the echelons. The measures that can eliminate this problem are discussed in Section 3.2.

3.1.1 Mathematical Model of the Supply Chain System

A sequential optimization approach is used in order to model the decentralized structure. The procedure consists of two main phases. The first phase, information flow, namely starts when the retailer echelon determines his optimal order quantities based on the forecasts he made. Then retailer echelon transmits only the order amount belonging to the current period to the distributor echelon. Distributor echelon decides on the optimal order amounts according to the current order placed by the retailer and his forecasts. In the second phase regarding the material flow, after receiving the order amount for the current period from the distributor echelon, manufacturers determine optimal raw material procurement, production and transportation amounts based on the information provided by the information sharing scheme they chose and the actual order information provided by the distributor echelon. By the initiation of the material transfer, distributor and retailer echelons update their inventory position enabling the distributor echelon determine his optimal transportation amount and the retailer echelon determine his optimal sales amounts. For the rest of the optimization horizon, the distributor and retailer echelons assume all of their orders will be fully satisfied by the immediate upstream echelon. The length of the optimization horizon is finite.

The sets regarding decision makers, products and time periods are as follows:

Sets:

Set of manufacturers I

Set of distributors J

Set of retailers K

Set of products P

Set of time periods T

Since each manufacturer produces a single product, sets i and p are equivalent. A parameter or variable indexed with p' is associated with the manufacturer whose index i' is equal to p'.

Parameters, decision variables of the corresponding decision makers are as follows:

Parameters of Manufacturers:

$fcastman_{p,k,t}$: demand forecast

pu_i: unit purchasing cost

y_i: production yield

v_i: variable production cost

f_i: fixed production cost

lp_i: production lead time

$PCap_i$: production capacity

rm_i: unit revenue

sal_i: unit salvage

$TCap_i$: total transportation capacity

$tr_{i,j}$: unit transportation cost

$g_{i,j}$: transportation lead time

int: annual interest rate

Decision Variables of Manufacturers:

$RP_{i,t}$; raw material purchased

$IR_{i,t}$: raw material inventory

$P_{i,t}$: production amount

$MInr_{i,t}$: finished goods inventory

$at_{i,j,t}$: transportation amount

$Sur_{i,j,t}$: surplus in the transportation amount

$Sla_{i,j,t}$: shortage in the transportation amount

$PS_{i,t}$; production run indicator

Parameters of Distributor Nodes:

$fcastdist_{p,k,t}$: demand forecast

$dt_{j,k}$: unit transportation cost

$sald_{p,j}$: unit salvage

$KD_{p,j}$: inventory capacity

$dl_{j,k}$: transportation lead time

$DTCap_{p,j}$: transportation capacity

$dmargin_{p,j}$: profit margin

Decision Variables of Distributor Nodes:

$atd_{p,j,k,t}$: transportation amount

$dorder_{i,j,t}$: order amount

$DInr_{p,j,t}$: inventory

$Surd_{p,j,k,t}$: surplus in the transportation amount

$Slad_{p,j,k,t}$: shortage in the transportation amount

Parameters of Retailer Nodes:

$KR_{p,k}$: inventory capacity

$fcast_{p,k,t}$: demand forecast

$demand_{p,k,t}$: customer demand

$quota_{j,k}$: quota for order amounts

$rmargin_{p,k}$: profit margin

Decision Variables of Retailer Nodes:

$order_{p,j,k,t}$: order amount

$RInr_{p,k,t}$: inventory

$s_{p,k,t}$: sales amount

$Surr_{p,k,t}$: surplus in the sales amount

$Slar_{p,k,t}$: shortage in the sales amount

Objective function and constraints for Manufacturers:

$revenue = \sum_j \sum_t rm_i \left(at_{i,j,t} - Sur_{i,j,t}\right)$

$salvage = \sum_j \sum_t sal_i Sur_{i,j,t}$

$raw\ material\ purchasing\ cost = \sum_t pu_i RP_{i,t}$

$raw\ material\ holding\ holding\ cost = \frac{int}{T} \sum_t pu_i IR_{i,t}$

$production\ cost = \sum_t \left(v_i P_{i,t} + f_i PS_{i,t}\right)$

$finished\ goods\ inventory\ holding\ cost = \frac{int}{T} \sum_t (v_i + pu_i) IFG_{i,t}$

$transportation\ cost = \sum_j \sum_t tr_{i,j} at_{i,j,t}$

$profitmanufacturer_i = \sum_j \sum_t rm_i \left(at_{i,j,t} - Sur_{i,j,t}\right) + \sum_j \sum_t sal_i Sur_{i,j,t} - \sum_t pu_i RP_{i,t} - \frac{int}{T} \sum_t pu_i IR_{i,t} - \sum_t \left(v_i P_{i,t} + f_i PS_{i,t}\right) - \frac{int}{T} \sum_t (v_i + pu_i) IFG_{i,t} - \sum_j \sum_t tr_{i,j} at_{i,j,t}$

The optimization problem of manufacturers is given as:

$max\ profitmanufacturer_i$

$s.t.$

$$P_{i,t} \leq PS_{i,t}PCap_i \qquad \forall i,t \ , \tag{3.1}$$

$$\sum_{t'=t-lp_i+1}^{t'=t+lp_i-1} PS_{i,t} \leq 1 \qquad \forall i,t \ , \tag{3.2}$$

$$\sum_j at_{i,j,t} \leq TCap_i \qquad \forall i,t \ , \tag{3.3}$$

$$Sur_{i,j,t} - Sla_{i,j,t} = at_{i,j,t} - dorder'_{i,j,t} \qquad \forall i,j,t \ , \tag{3.4}$$

$$IR_{i,t} = IR_{i,t-1} + RP_{i,t} - P_{i,t} \qquad \forall i, \forall t = 1..T \ , \tag{3.5}$$

$$MInr_{i,t} = MInr_{i,t-1} + y_i P_{i,t-lp_{il}} - \sum_j at_{i,j,t} \qquad \forall i,l,\forall t = 1..T \ , \tag{3.6}$$

$$RP_{i,0}, IR_{i,0}, PS_{i,0}, at_{i,j,0} = 0 \qquad \forall i \ , \tag{3.7}$$

$$MInr_{i,0} = MInr'_i \qquad \forall i \ , \tag{3.8}$$

$$RP_{i,t}, IR_{it}, P_{i,t}, MInr_{i,t}, at_{i,j,t}, Sur_{i,j,t}, Sla_{i,j,t} \geq 0 \qquad \forall i,j,t, \tag{3.9}$$

$$PS_{i,t} \in \{0,1\} \qquad \forall i,t \ . \tag{3.10}$$

Constraints (3.1) represents the production capacities of the manufacturers. There can not be simultaneous production runs if the production line is busy and this condition is handled by constraint (3.2). Constraints (3.3) stand for total transportation capacity (fleet size is fixed). The discrepancy between the shipment amount and the actual amount in the order placed by the distributor nodes is calculated in constraints (3.4). The value of $dorder'_{i,j,t}$ is fixed for the current period and its calculation for the remaining periods depend on the IS scheme being used. Constraints (3.5) and (3.6) handles raw material and finished goods inventory balances respectively. Constraints (3.7) set the initial values of raw materials purchased, raw material inventory, production run indicator and transportation amount to zero. Constraints (3.8) sets the initial finished goods inventory amount.

Objective function and constraints for Distributor Nodes:

$revenue = \sum_{i=p}\sum_{j}\sum_{k}\sum_{t}(1+dmargin_{p,j})rm_i(atd_{p,j,k,t} - Surd_{p,j,k,t})$

$salvage = \sum_{j}\sum_{k}\sum_{t} sald_{p,j}Surd_{p,j,k,t}$

$planned\ purchasing\ cost = \sum_{i=p}\sum_{j}\sum_{t} rm_i dorder_{i,j,t}$

$actual\ purchasing\ cost = \sum_{i=p}\sum_{j}\sum_{t} rm_i(at'_{i,j,t} - Sur'_{i,j,t})$

$holding\ cost = \frac{int}{T}\sum_{i=p}\sum_{j}\sum_{t} rm_i DInr_{p,j,t}$

$transportation\ cost = \sum_{j}\sum_{k}\sum_{t} dt_{j,k}atd_{p,j,k,t}$

$profitdistributor_p = \sum_{i=p}\sum_{j}\sum_{k}\sum_{t}(1+dmargin_j)rm_i(atd_{p,j,k,t} - Surd_{p,j,k,t}) +$
$\sum_{j}\sum_{k}\sum_{t} sald_{p,j}Surd_{p,j,k,t} - \Big[\sum_{i=p}\sum_{j}\sum_{t} rm_i order_{i,j,t}\ \Lambda\ \sum_{i=p}\sum_{j}\sum_{t} rm_i(at'_{i,j,t} - Sur'_{i,j,t})\Big] -$
$\frac{int}{T}\sum_{i=p}\sum_{j}\sum_{t} rm_i DInr_{p,j,t} - \sum_{j}\sum_{k}\sum_{t} dt_{j,k}atd_{p,j,k,t}$

The optimization problem of distributor echelon is given as:

$max\ profitdistributor_p$

$s.t.$

$$DInr_{p,j,t} \le KD_{p,j} \qquad \forall j,p,t\ , \tag{3.11}$$

$$DInr_{p,j,t} = DInr_{p,j,t-1} + \sum_{i=p} dorder_{i,j,t-g_{i,j}} - \sum_{k} atd_{p,j,k,t} \qquad \forall j,p,\forall t = 1..T\ , \tag{3.12}$$

$$DInr_{p,j,t} = DInr_{p,j,t-1} + \sum_{i=p}(at'_{i,j,t-g_{i,j}} - Sur'_{i,j,t-g_{i,j}}) - \sum_{k} atd_{p,j,k,t} \qquad \forall j,p,\forall t = 1..T\ , \tag{3.13}$$

$$Surd_{p,j,k,t} - Slad_{p,j,k,t} = atd_{p,j,k,t} - order'_{p,j,k,t} \qquad \forall j,k,p,t\ , \tag{3.14}$$

$$\sum_k atd_{p,j,k,t} \leq DTCap_{p,j} \qquad \forall j,p,t\ , \tag{3.15}$$

$$atd_{p,j,k,0} = 0 \qquad \forall j,k,p\ , \tag{3.16}$$

$$DInr_{p,j,0} = DInr'_{p,j} \qquad \forall j,k,p\ , \tag{3.17}$$

$$atd_{p,j,k,t}, dorder_{i,j,t}, DInr_{p,j,t}, Surd_{p,j,k,t}, Slad_{p,j,k,t} \geq 0 \qquad \forall i,j,k,p,t\ . \tag{3.18}$$

Constraints (3.11) represent inventory capacity. Constraints (3.12) and (3.13) are to maintain inventory balance for the first and second phase of the optimization, respectively. Constraints (3.14) enable obtaining the discrepancy between the amount shipped by the distributor nodes and the actual amount in the order placed by the retailer nodes. The value of $order'_{p,j,k,t}$ is fixed for the current period and its calculation for the remaining periods depend on the IS scheme being used. Constraints (3.15) constitute the total transportation capacity. Constraints (3.16)sets the initial values of transportation amount to zero. Finally, constraints (3.17) determine initial inventory levels.

Objective function and constraints for Retailer Nodes:

$revenue = \sum_{i=p}\sum_j\sum_k\sum_t (1 + dmargin_{p,j} + rmargin_{p,k}) rm_i (s_{p,k,t} - Surr_{p,k,t})$

$planned\ purchasing\ cost = \sum_{i=p}\sum_j\sum_k\sum_t (1 + dmargin_{p,j}) rm_i order_{p,j,k,t}$

$actual\ purchasing\ cost = \sum_{i=p}\sum_j\sum_k\sum_t (1 + dmargin_{p,j}) rm_i (atd'_{p,j,k,t} - Surd'_{p,j,k,t})$

$holding\ cost = \frac{int}{T}\sum_{i=p}\sum_j\sum_k\sum_t (1 + dmargin_{p,j}) rm_i RInr_{p,k}$

$profitretailer_p = \sum_{i=p}\sum_k\sum_t (1 + dmargin_{p,j} + rmargin_{p,k}) rm_i (s_{p,k,t} - Surr_{p,k,t}) - \Big[\sum_{i=p}\sum_j\sum_k\sum_t (1 + dmargin_{p,j}) rm_i order_{p,j,k,t}\ \Lambda\ \sum_{i=p}\sum_j\sum_k\sum_t (1 + dmargin_{p,j}) rm_i (atd_{p,j,k,t} - Surd_{p,j,k,t})\Big] - \frac{int}{T}\sum_{i=p}\sum_j\sum_k\sum_t (1 + dmargin_{p,j}) rm_i RInr_{p,k}$

The optimization problem of retailer echelon is given as:

$max\ profitretailer_p$

$s.t.$

$$RInr_{p,k,t} \leq KR_{p,k} \qquad \forall k, p, t \ , \tag{3.19}$$

$$RInr_{p,k,t} = RInr_{p,k,t-1} + \sum_j order_{p,j,k,t-dl_{j,k}} - s_{p,k,t} + Surr_{p,k,t} \qquad \forall k, p, \forall t = 1..T \ , \tag{3.20}$$

$$RInr_{p,k,t} = RInr_{p,k,t-1} + \sum_j (atd'_{p,j,k,t-dl_{j,k}} - Surd'_{p,j,k,t-dl_{j,k}}) - s_{p,k,t} + Surr_{p,k,t} \qquad \forall k, p, \forall t = 1..T \ , \tag{3.21}$$

$$s_{p,k,t} - fcast_{p,k,t} = Surr_{p,k,t} - Slar_{p,k,t} \qquad \forall k, p, t \ , \tag{3.22}$$

$$order_{p,j,k,t-dl_{j,k}} \leq \sum_{j'} order_{p,j',k,t-dl_{j',k}} quota_{j,k} \qquad \forall j, k, p, t \ , \tag{3.23}$$

$$s_{p,k,0} = 0 \qquad \forall k, p \ , \tag{3.24}$$

$$RInr_{p,k,0} = RInr'_{p,k} \qquad \forall k, p \ , \tag{3.25}$$

$$s_{p,k,t}, order_{p,j,k,t}, RInr_{p,k,t}, Surr_{p,k,t}, Slar_{p,k,t} \geq 0 \qquad \forall j, k, p, t \ . \tag{3.26}$$

Constraints (3.19) represents inventory capacity. Constraints (3.20) and (3.21) maintain inventory balance for the first and second phases of the optimization respectively. The discrepancy between sales and demand amount is calculated in constraints (3.22). The quotation applied to distributor nodes is handled by constraints (3.23). In more detail, an order given by a retailer node that will be available for sale at period t can not exceed a specified portion of the total amount in the orders placed by the same retailer which are also going to be available at the same period. Constraints (3.24) sets the initial values of sales amount to zero. Constraints (3.25) sets the initial inventory value.

3.1.2 Model Predictive Control

MPC is a collection of control methods applied concurrently with a mathematical model with the aim of optimizing an objective function. Receding horizon approach is widely used in MPC studies. In Receding Horizon Predictive Control approach, at each time instant, past and present information about the parameters and the overall state of the system is utilized for predicting future (for the rest of the optimizing horizon) parameters of the system and calculating the necessary control actions based on those predictions (see Camacho and Bordons [2004]). MPC has wide range of applications primarily in chemical process industry, however it can provide great benefits in supply chain modeling and optimizing and such examples were referred in Section 2.1.

A general framework about how MPC approaches operate is shown in Figure 3.1. For the remaining N horizons, future outputs ($y(t+k|t)$, $k = 1...N$) are predicted based on the existing information and future control actions ($u(t+k|t)$, $k = 1...N$). The control actions are calculated by optimizing the corresponding objective function of the model with the adopted control strategy. Naturally, a system is not composed of mere control actions. State variables are also required for storing information as the consequences of those control actions and handling the relationship between different control actions.

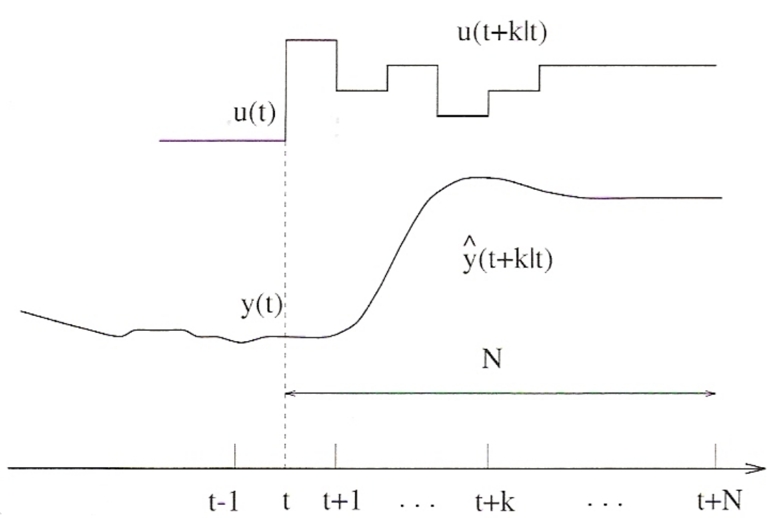

Figure 3.1: General RHPC Framework (Camacho and Bordons [2004])

In this study, proposed supply chain model including the parameters, variables, objective functions and constraints of the corresponding decision makers is embedded in a RHPC strategy. At each time instant of the optimizing horizon, the proposed sequential optimization approach (see Section 3.1.1) is applied. A detailed variable classification can be seen in Table 3.1.

Table 3.1: Variable Classification of the Supply Chain Model

	Information Flow		**Material Flow**	
Decision Makers	**State Variable**	**Control Variables**	**State Variables**	**Control Variables**
Manufacturers			$IR_{i,t}$	$RP_{i,t}$
			$MInr_{i,t}$	$P_{i,t}$
			$Sur_{i,j,t}$	$at_{i,j,t}$
			$Sla_{i,j,t}$	$PS_{i,t}$
Distributors		$dorder_{i,j,t}$	$DInr_{p,j,t}$	$atd_{p,j,k,t}$
			$Surd_{p,j,k,t}$	
			$Slad_{p,j,k,t}$	
Retailers		$order_{p,j,k,t}$	$RInr_{p,k,t}$	$s_{p,k,t}$
			$Surr_{p,k,t}$	
			$Slar_{p,k,t}$	

To sum up, at each time instance (at the start of the current receding horizon) MILP problems of different decision makers are solved in the aforementioned order, first for the information flow and second for the material flow, as deterministic problems since the decision makers assume their forecasts will exactly hold which is actually the case in real-life problems. The optimization approach is summarized in Figure 3.2.

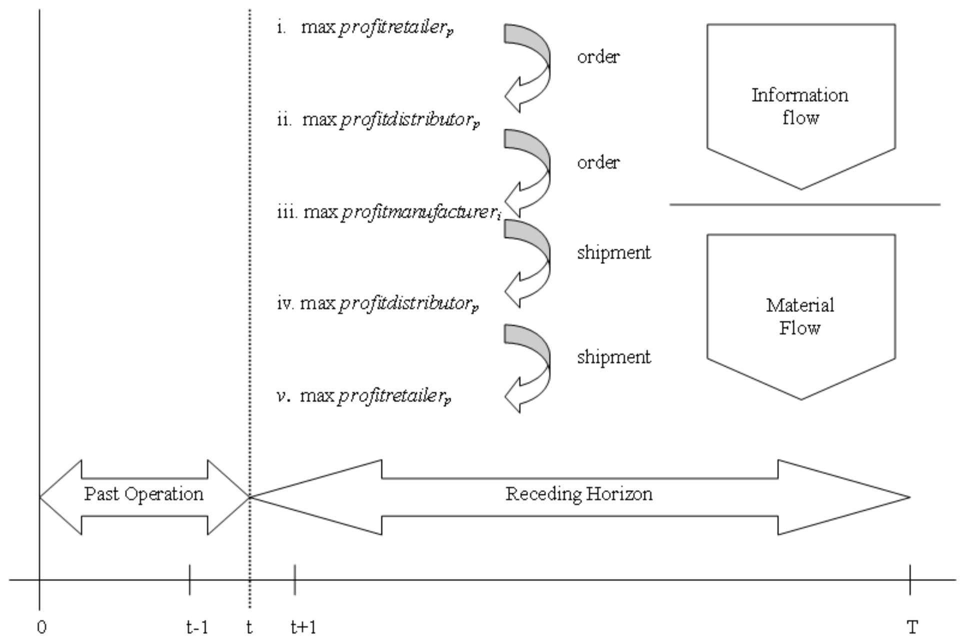

Figure 3.2: Optimization Approach

3.2 Information Sharing Schemes

There are three information sharing schemes in this study. First one is the base case, no information sharing scheme, namely. Other two information sharing schemes are based on sharing demand information and they are:

- future demand (forecast) information sharing
- historic demand information sharing schemes

IS is organized as a vertical relationship since the products belonging to different manufacturers remain mutually exclusive throughout the system and other echelons are horizontally centralized. Therefore horizontal information carries no value at all and retailer nodes share information with distributor nodes and manufacturers.

Demand distributions for different retailer nodes differentiate in individual parameters. However overall structures are quite similar and significantly seasonal with a fixed period.

An example of a demand structure with periodicity 13, for an arbitrary retailer node can be seen in Figure 3.3. At $t = 0$ demand is set to a level value. For the rest of the horizon, if the periodicity is taken as p, at each $(p \times k + 1)th, k = \{1, 2, ...\}$, period, the demand is set to $demand(p \times k) - (p - 1) \times increment + w(\mu, \sigma^2)$ where $increment$ is a constant parameter and w is a random shock that has standard normal distribution ($\mu = 0$). In general case, $demand(k + 1) = demand(k) + (k + 1)(mod(p + 1)) \times increment + w(\mu, \sigma^2)$ if $(k + 1)(mod(p + 1)) \neq 0$.

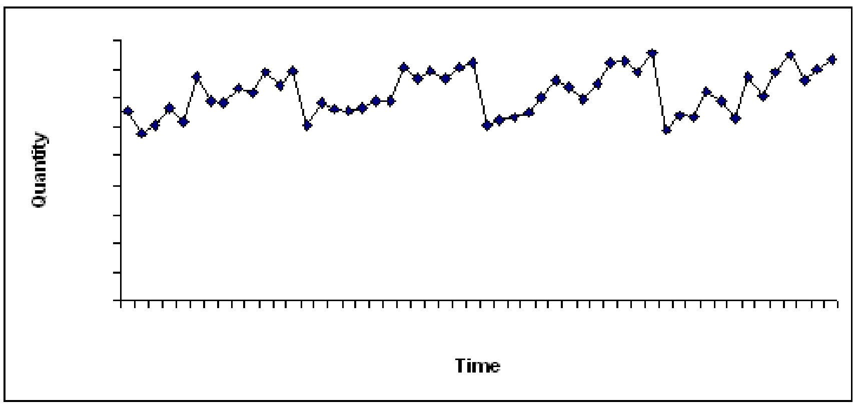

Figure 3.3: An Instance for the Demand Process

3.2.1 No Information Sharing

In this scheme, the only information transferred among different echelons is the order amounts belonging to the current period. While retailer nodes can make forecasts based on the historic and current demand information, other nodes can depend on only the information obtained from the orders placed by their downstream neighbors. Therefore manufacturers and distributor nodes use Kalman Filtering for forecasting future orders (Brown and Hwang [1992]). By using Kalman filtering, they assume that the order quantities from immediate downstream echelon will be equal to the quantities in the current period until the end of remaining optimization horizon.

3.2.2 Future Demand (Forecast) Information Sharing

In this scheme, retailer nodes share their forecasts for the rest of the optimization horizon. Retailers are assumed to be using Winter's seasonal forecasting method (see Chopra and Meindl [2002]) due to the particular design of the demand process. Underlying demand process has no trend, hence only the seasonal part of the method is utilized. If the periodicity of the data in consideration is p, with the initial estimates of Level (L_0) and Seasonality factors ($S_1, S_2, ..., S_p$) forecasts (F_t) are performed as follows:

$$F_{t+1} = L_t S_{t+1} \text{ and } F_{t+l} = L_t S_{t+l} \ , \tag{3.27}$$

When the demand for $t+1$ th period (D_{t+1}) is realized, by using α and γ, the smoothing constants for level and seasonality factor respectively, the estimations for Level and Seasonality factors are updated as follows:

$$L_{t+1} = \alpha(D_{t+1}/S_{t+1}) + (1-\alpha)L_t \ , \tag{3.28}$$

$$S_{t+p+1} = \gamma(D_{t+1}/L_{t+1}) + (1-\gamma)S_{t+1} \text{ and } \alpha, \gamma \in [0,1] \ . \tag{3.29}$$

Access to this information enables manufacturers and distributor nodes implicitly make the following updates in equations 3.4 and 3.14, respectively.

$$dorder'_{i,j,t} = \sum_{p=i} \sum_{k} fcast_{p,k,t+g(i,j)+dl(j,k)} quota_{j,k} \qquad \forall i, j, \forall t = (t'+1)..(T-t') \ , \tag{3.30}$$

$$order'_{p,j,k,t} = \sum_{p=i} fcast_{p,k,t+dl(j,k)} quota_{j,k} \qquad \forall i, j, k, \forall t = (t'+1)..(T-t') \ . \tag{3.31}$$

3.2.3 Historic Demand Information Sharing

In this scheme, retailer nodes share historic demand information prior to the optimization horizon. Therefore other decision makers can produce their own forecasts. In this study manufacturers and distributors are assumed to be using ARMA method for modeling demand process and forecasting future values.

For a time series of data X_t, if the data is stationary, an ARMA model is consistent to use for predicting future values of the data. Since the demand structure particular for this study features stationarity (fixed mean) it is convenient to use the method. The method consists of two parts: Auto Regressive model and Moving Average model. The combined ARMA model is as follows:

$$X_t = c + \epsilon_t + \sum_{i=1}^{p} \varphi_i X_{t-i} + \sum_{i=1}^{q} \theta_i \epsilon_{t-i} \ . \tag{3.32}$$

where c is a constant, ϵ_t are independent and identically distributed random variables sampled from a normal distribution with zero mean and variance σ^2, p is the order of auto regressive model and q is order of moving average model, φ_i and θ_i are the parameters for auto regressive and moving average models, respectively. ARMA models used in this study are obtained by a software called ITSM provided in the textbook by Brockwell and Davis [2002]. The demand process in this study is assumed to be significantly seasonal hence not stationary. However by using the *difference* tool provided by ITSM, the seasonality is eliminated from the process. The demand process shown in Figure 3.3 is transformed into the one exhibited in Figure 3.4.

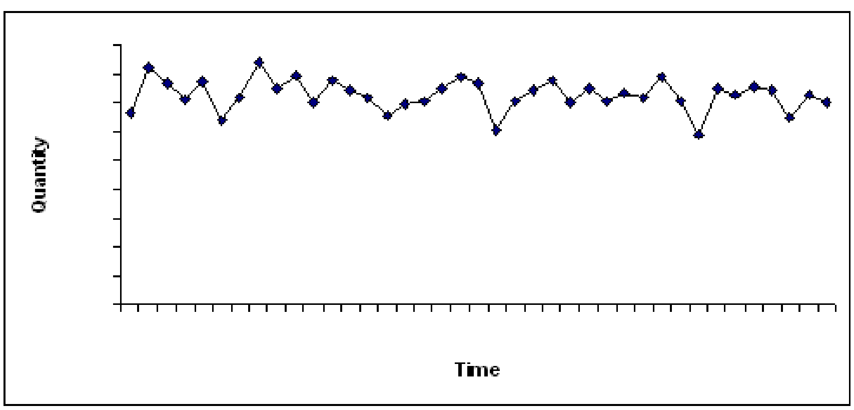

Figure 3.4: An Instance for the Transformed Demand Process

Access to this information enables manufacturers and distributor nodes implicitly make the following updates Equations 3.4 and 3.14 respectively.

$$dorder'_{i,j,t} = \sum_{p=i} \sum_{k} fcastman_{p,k,t+g(i,j)+dl(j,k)} quota_{j,k} \qquad \forall i,j,\forall t = (t'+1)..(T-t') \ , \tag{3.33}$$

$$order'_{p,j,k,t} = \sum_{p=i} fcastdist_{p,k,t+dl(j,k)} quota_{j,k} \qquad \forall i,j,k,\forall t = (t'+1)..(T-t') \ . \tag{3.34}$$

In summary, the difference between the performances of decision makers due to using either FDIS or HDIS is basically the difference between the forecasting accuracies of Winter's seasonal forecasting method and utilization of ARMA models.

3.3 Numerical Analysis

In this chapter, the mathematical model with the proposed optimization approach is applied in order to analyze the effects of the information sharing schemes presented in the previous sections. The Supply Chain in this section is a three echelon, decentralized one with two separate manufacturers, a distributor echelon (horizontally centralized) with three nodes, a retailer echelon (horizontally centralized) with five nodes, incapacitated suppliers and customers with a seasonal demand process with period 13 (see Figure 3.5).

As stated earlier, suppliers and customers are not modeled as decision makers. Two manufacturers differ only in transportation attributes. First manufacturer has longer transportation lead time, larger transportation capacity and lower unit transportation cost (see Table 3.2. Modeling two suppliers with non-substitutable products is for mere computational purposes. When the model is run, the results regarding the comparison of two manufacturers based on their unique transportation characteristics are obtained concurrently for both manufacturers. GAMS and CPLEX are used as the modeling and solving platforms (with relative gap: 0.03%) and solution statistics can be found in Appendix.

The table summarizing the effects of different information sharing schemes on profit levels belonging to different decision makers are given in Tables 3.3 and 3.6. The values belonging to distributors and retailers denote aggregate value for the corresponding echelon. $Product_i$ relates the field shown with the product supplied by $Manufacturer_i$ for all tables and figures throughout the study. Furthermore, profit values are scaled based on the minimum value for the particular table they are presented in.

Table 3.2: Manufacturer Parameters

Parameter	$Manufacturer_1$	$Manufacturer_2$
Transportation Lead Time	3	1
Transportation Capacity	14000	12000
Average Transportation Cost	8	18

Table 3.3: Effects of IS on Manufacturer Profit Levels

	IS Schemes	$Manufacturer_1$	$Manufacturer_2$
	NIS	1.90	1.00
IS with Distributor Echelon	**FDIS**	1.97	1.03
	HDIS	1.93	1.04
IS with Manufacturers	**FDIS**	1.98	1.35
	HDIS	2.00	1.36
IS with Both Echelons	**FDIS**	2.23	1.38
	HDIS	2.20	1.36

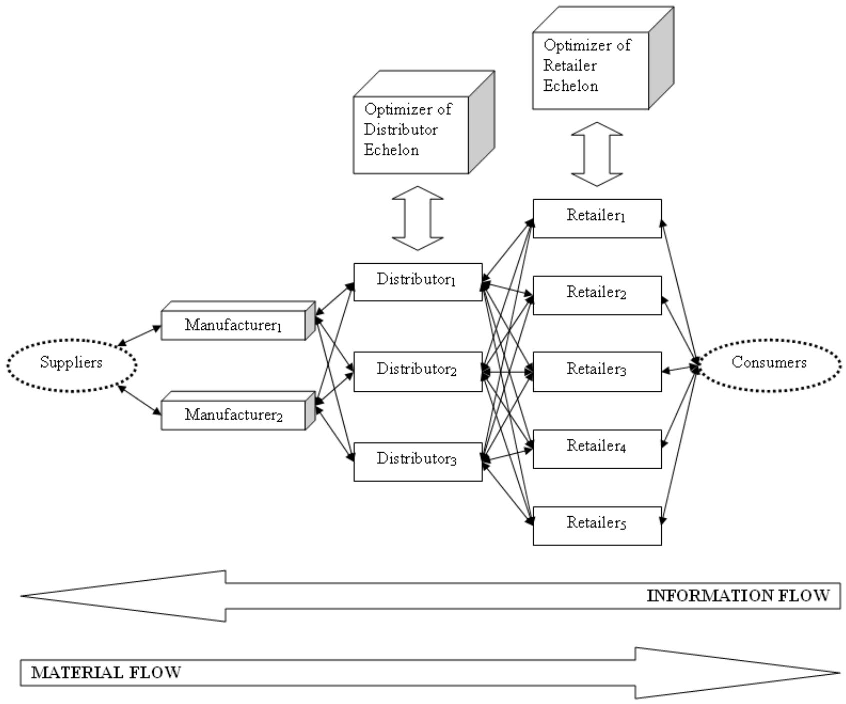

Figure 3.5: Supply Chain System in Consideration

According to Table 3.3 IS yields better performance in terms of profits for all of the different cases. When information is shared with a single echelon, manufacturers favor the situation where information is shared with them. However when information is shared with both distribution echelon and manufacturers best profit levels for manufacturers are achieved. The reason behind this outcome is the convergence of the operation of supply chain system to the centralized case. When information is shared with only manufacturers, despite better batch sizes of the manufacturers, in terms of timing and amount, inaccurate orders placed by the distributor nodes constitute a setback for smooth material transfer. Due to the seasonal behavior of customer demand, orders within a demand cycle should be increasing until the end of the cycle. However since distributor nodes assume future orders that will be placed by retailer nodes will be same the as the ones in the current period, they do not place orders with sufficient sizes even if manufacturers have the capability to supply more products than they are doing in this situation. A similar problem is faced when information is shared with only distributor echelon. Regardless of the accurate orders placed by distributor nodes, manufacturers do not produce in sufficient batches since they lack accurate demand information.

There is no significant dominance of FDIS and HDIS throughout the cases which means they possess equivalent capabilities regarding accounting for seasonal forecasting. For instance, when information is shared with only distributor echelon, FDIS is better but when information is shared with only manufacturers HDIS is better. When two manufacturers are compared, second manufacturer experiences greater relative improvement (see table 3.4). This is a result of the greater increase in his service level and is discussed in the following paragraphs.

Table 3.4: Relative Improvement in Manufacturer Profit Levels with IS

	IS Schemes	$Manufacturer_1$	$Manufacturer_2$
	NIS	Base	Base
IS with Distributor Echelon	**FDIS**	3.6%	3.3%
	HDIS	2%	4%
IS with Manufacturers	**FDIS**	4.1%	35.3%
	HDIS	5.2%	35.5%
IS with Both Echelons	**FDIS**	17.5%	38.4%
	HDIS	15.7%	36.1%

Service level is another important performance measure that should be considered in supply chain analysis. Intuitively there exists a positive correlation between service and inventory level and since inventory holding has a cost associated with it, there is a trade-off between service level and inventory holding cost. The summary of the effects of IS on service and inventory levels is presented in Table 3.5. Inventory levels are scaled based on the minimum value.

Table 3.5 exhibits interesting results regarding relationship between manufacturer properties, IS Schemes, inventory and service levels. The correlation between service levels and IS schemes is quite similar with the one between profits and IS schemes. This is quite

Table 3.5: Effects of IS on Manufacturer Service and Inventory Levels

		$Manufacturer_1$		$Manufacturer_2$	
	IS Schemes	**SL**	**Total Inventory**	**SL**	**Total Inventory**
	NIS	0.90	1.17	0.85	1.04
IS with Distributor Echelon	**FDIS**	0.90	1.07	0.88	1.00
	HDIS	0.89	1.14	0.87	1.01
IS with Manufacturers	**FDIS**	0.91	1.53	0.98	1.33
	HDIS	0.92	1.49	0.98	1.31
IS with Both Echelons	**FDIS**	0.98	1.10	1.00	1.25
	HDIS	0.99	1.14	1.00	1.30

intuitive because IS schemes only differ in the way that demand information possessed by retailer nodes is shared with other echelons. There is no cost difference among IS schemes hence the increase in profit levels are caused by the increase in service levels. However relationship between service and inventory levels is not common for different manufacturers in a same IS Scheme. When information is shared with only distributor echelon inventory levels of both manufacturers tend to decrease due to more accurate order amounts of distributor nodes. On the other hand, while service level of the first manufacturer does not change, an increase emanates in the service level of the second manufacturer. This situation is closely related to transportation lead times of the manufacturers. When switching from NIS scheme to any of the schemes in IS with distributor echelon case, total order amount required to be satisfied by the first manufacturer increases. Conversely, amount of finished good that should be supplied by the second manufacturer almost remains same. Since transportation lead time of the second manufacturer is shorter, the difference (most of the time positive due to the seasonal structure of the demand process) between the amounts in the orders placed by distributor nodes in the same periods of the optimization horizon under NIS scheme and any of schemes in IS with distributor echelon is not as significant as for the first manufacturer with longer transportation lead time. Consequently, although production amounts for both manufacturers increase, ordering behavior of the distributor nodes generate different outcomes in the service levels of different manufacturers (see Figures 3.6 and 3.7). If information is shared with only manufacturers, inventory levels of both manufacturers increase as the result of more accurate end demand forecasts they made and same order amounts of distributor nodes lacking sufficient demand information. Despite the incline in the inventory levels service level of the first manufacturer do not increase significantly because of his long transportation lead time. He can not satisfy the orders placed by distributor nodes near to the end of optimization horizon. Second manufacturer however utilizes the advantage of being more flexible in terms of shipment time hence faces substantial increase in his service level. Finally, when information is shared among all participants of the system, second manufacturer satisfies all of his requirements and first manufacturer almost shows the same performance. The different alterations in inventory levels can be explained in a similar way as the one in the case where IS is between distributor and retailer echelons only. Inventory level of the first manufacturer is almost equal in two cases since production amounts increase together with the order amounts of distributor nodes. The increase in the inventory level of the second manufacturer is a consequence of less order variance of distributor nodes due to the shorter transportation lead time. Increasing production while facing similar order amounts yields larger inventory for the second manufacturer.

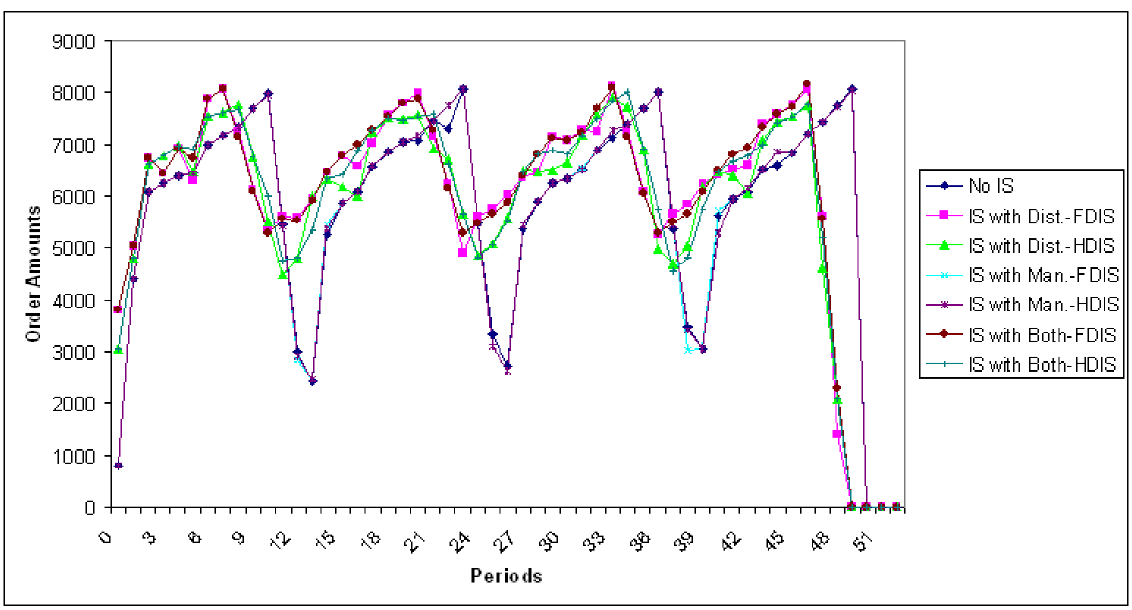

Figure 3.6: Ordering Profile of Distributor Echelon for $Product_1$

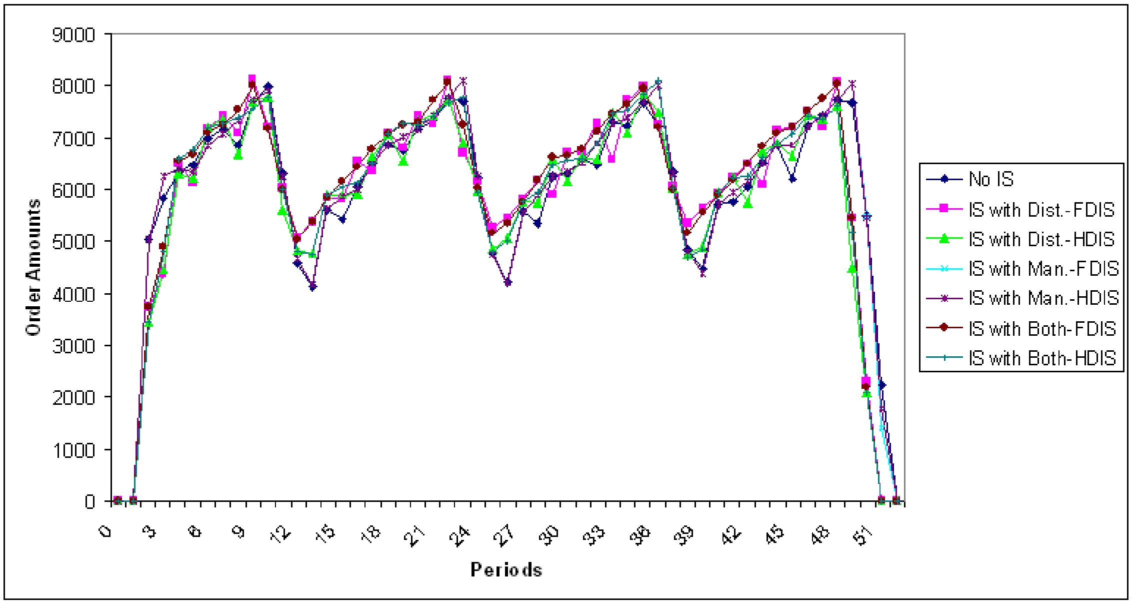

Figure 3.7: Ordering Profile of Distributor Echelon for $Product_2$

According to Table 3.6 if information had to be shared with a single echelon, distributor echelon would prefer him to be IS party. However in that case retailer echelon achieves higher profit if he shares information with manufacturers. Even if IS with only distributor echelon yields higher profit for the product supplied by the first manufacturer and IS with only manufacturers provide higher profit for other product, comparison of the total profits of retailer echelon under different IS scenarios indicate that IS with manufacturers is better since average service levels for both echelons are also higher. Finally, IS with both echelons is the dominant case yielding highest total profit for the retailer echelon as a result of highest average service levels.

As in the case with manufacturers, characterizing the relationships between service and profit levels of distributor and retailer nodes is not simple. Results (see Table 3.7) related with the product supplied by the first manufacturer show that service and profit levels are positively correlated for both distributor and retailer echelons. For the second product, service and profit levels of the retailer echelon are also positively correlated. But the service and profit levels of the distributor echelon regarding the product supplied by the manufacturer with shorter lead time are negatively correlated. While IS with manufacturers

Table 3.6: Effects of IS on Distributor and Retailer Echelon Profit Levels

		Distributor		*Retailer*	
	IS Schemes	$Product_1$	$Product_2$	$Product_1$	$Product_2$
	NIS	1.00	2.26	2.02	4.05
IS with Distributor Echelon	**FDIS**	1.84	3.65	2.22	4.37
	HDIS	1.80	3.58	2.15	4.24
IS with Manufacturers	**FDIS**	1.43	3.05	2.12	4.50
	HDIS	1.46	3.08	2.14	4.52
IS with Both Echelons	**FDIS**	1.92	3.88	2.40	4.85
	HDIS	1.92	3.86	2.39	4.81

produces less profit than IS with distributor echelon does, comparing service level presents contradictory outcomes. This is related with the utilization of the initial inventories of the distributor nodes. Even if revenue generated when IS with manufacturers is ongoing, is greater, purchasing cost increases more than revenue does. In the case where information is only available to manufacturers, distributor nodes with short lead times salvage their initial inventory because retailer nodes do not place any orders to them instead retailers use their own initial inventories to avoid purchasing cost. By using Kalman Filtering those distributor nodes assume there will not be any orders placed by the retailer nodes till the end of the optimization horizon so they try to dispose of useless inventory. Eventually when they face orders placed by retailer nodes they have to purchase from manufacturers as a result of lacking inventory and incur a purchasing cost greater than inventory holding cost which would incur if the initial inventory was not disposed of.

When information is shared with a single echelon, service levels of distributor and retailer echelons are inversely affected based on the related product and whom information is shared with. For instance, regardless of the information sharing scheme chosen, IS with only distributor echelon yields higher service levels for both distributor and retailer echelons for the first product but same strategy yields lower service levels for both distributor and retailer echelons than sharing information with only manufacturers for the second product.

Once again, different lead times of the manufacturers are the major factors for this result. When distributor nodes place an order to the second manufacturer, whether they have access to demand information or not, they do not end up with significant forecast errors due to the short lead time of the corresponding manufacturer which can be interpreted as low order variance. Therefore, since IS with only manufacturers induce larger batch sizes and by the additional impact of low order variance service level increases. For the first product however, even if IS with only manufacturers results in larger production amounts forecasts made by the distributor echelon contain high errors and resulting orders hinder sufficient product transfer to the retailer nodes and make distributor nodes end up with low service levels. Same effect reflects on retailer echelon because his service level is directly related with the service level of distributor echelon.

Table 3.7: Effects of IS on Distributor and Retailer Echelon Service Levels

		Distributor		*Retailer*	
	IS Schemes	$Product_1$	$Product_2$	$Product_1$	$Product_2$
	NIS	0.80	0.80	0.77	0.77
IS with Distributor Echelon	**FDIS**	0.89	0.86	0.85	0.83
	HDIS	0.85	0.83	0.82	0.80
IS with Manufacturers	**FDIS**	0.84	0.94	0.81	0.90
	HDIS	0.85	0.94	0.81	0.90
IS with Both Echelons	**FDIS**	0.97	0.99	0.93	0.95
	HDIS	0.96	0.97	0.92	0.93

3.3.1 Bullwhip Effect

Bullwhip effect is one of the most used performance measures for quantifying information distortion throughout a supply chain system. Bullwhip effect faced by a node is commonly defined as the ratio of variance of outgoing orders to the variance of incoming orders. The aim in analyzing bullwhip effect is to perceive the magnitude of information distortion and which echelon suffers from the consequences regarding that distortion while information flows through the system. In this study bullwhip effect is measured for retailer and distributor echelons since they have an explicit ordering process. Bullwhip effect for retailer and distributor echelons are calculated by equations 3.35 and 3.36, respectively.

$$BW(Retailer)_p = \frac{var(\sum_j \sum_k order_{p,j,k,t})}{var(\sum_k demand_{p,k,t})} \qquad \forall p \ , \tag{3.35}$$

$$BW(Distributor)_p = \frac{var(\sum_{i=p} \sum_j dorder_{i,j,t})}{var(\sum_j \sum_k order_{p,j,k,t})} \qquad \forall p \ . \tag{3.36}$$

There are certain factors that amplify bullwhip effect. One of the most encountered factors can be called as preventive ordering. When a supply chain participant faces a shortage in a previous period, next period he tends to place orders that contain higher amounts than his demand forecasts. He somehow tries to preserve himself from possible stockouts by acting in the way explained above. Particularly in this study, if preventive ordering is used retailers and distributors update their optimal order amounts by adding the shortage amount in the previous period to the order amount for the current period (see equations 3.37 and 3.38).

$$order'_{p,j,k,t} = order_{p,j,k,t} + Slar_{p,k,t-1} quota_{j,k} \qquad \forall p, j, k, \forall t = 1..T \ , \tag{3.37}$$

$$dorder'_{i,j,t} = dorder_{i,j,t} + \sum_k \sum_{p=i} Slad_{p,j,k,t-1} \qquad \forall i, j, \forall t = 1..T \ . \tag{3.38}$$

Furthermore if a distributor node ships more than the amount in the order of the target retailer node, surplus amount is added to inventory of the distributor node. A new variable, $salvad_{p,j,t}$, is added to the system to represent salvage amount of distributor node j in period t. Updated versions of equations 3.12 and 3.13 are equations 3.39 and 3.40, respectively.

$$\begin{aligned} DInr_{p,j,t} &= DInr_{p,j,t-1} + \sum_{i=p} dorder_{i,j,t-g_{i,j}} - \sum_k (atd_{p,j,k,t} - Surd_{p,j,k,t}) \\ &\quad - salvad_{p,j,t} \qquad \forall j, p, \forall t = 1..T \ , \end{aligned} \tag{3.39}$$

$$DInr_{p,j,t} = DInr_{p,j,t-1} + \sum_{i=p}(at'_{i,j,t-g_{i,j}} - Sur'_{i,j,t-g_{i,j}}) - \sum_{k}(atd_{p,j,k,t} - Surd_{p,j,k,t}) - salvad_{p,j,t} \qquad \forall j,p,\forall t = 1..T \ . \tag{3.40}$$

Bullwhip effect regarding distributor and retailer echelons, different products and IS schemes and strategies are summarized in Tables 3.8 and 3.9. When preventive ordering is excluded, bullwhip effect on the retailer echelon is independent of the IS schemes and strategies for both products. On the other hand, bullwhip effect on the distributor echelon varies with product type, IS scheme and strategy. Previously, the relationship between ordering behavior of the distributor nodes for different products and transportation lead times of the corresponding manufacturer was stated. When information is shared with distributors only or both echelons, the reduction in the variance of orders placed by the distributor nodes is more significant for $product_1$ due to larger transportation lead time. At the same time, for the last periods in the optimization horizon, distributor nodes do not place orders knowing that also retailer nodes will not place orders (orders that are going to be certainly unsatisfied within optimization horizon due to transportation lead times) since at each time instance retailer echelon shares his forecasts. Consequently these zero quantity orders increase order variance of distributor nodes. Since variance reduction due to sufficient information in orders related to $product_2$ is not significant, bullwhip effect increases for $product_2$ when any type of demand information is accessible to distributor echelon. On the other hand, if information is shared with only manufacturers, there are simultaneous increases in the bullwhip effect on distributor echelon for both products. This result is caused by combined effects of inaccurate distributor orders and fulfillment of these orders by manufacturers. Especially, in periods when seasonal cycles restart distributor nodes are left with excess inventory since they over estimate the orders that will be given in those periods. Having excess inventory at hand, they place orders in small amounts increasing the order variance hence the bullwhip effect.

In the case of preventive ordering, under NIS Scheme, bullwhip effect for the retailer and distributor echelons significantly increases due to low service levels. However specifically for distributor echelon, bullwhip effects fall even under the values for the case in which preventive ordering is excluded. This result is not due to greater variance reduction in order

Table 3.8: Bullwhip Effect on Distributor and Retailer Echelons without Preventive Ordering

		Distributor		*Retailer*	
	IS Schemes	$Product_1$	$Product_2$	$Product_1$	$Product_2$
	NIS	2.00	1.50	1.31	1.31
IS with Distributor Echelon	**FDIS**	1.87	1.79	1.31	1.31
	HDIS	1.86	1.80	1.31	1.31
IS with Manufacturers	**FDIS**	2.05	1.62	1.31	1.30
	HDIS	2.04	1.60	1.31	1.30
IS with Both Echelons	**FDIS**	1.84	1.86	1.31	1.30
	HDIS	1.90	1.88	1.31	1.30

amounts of distributor nodes, rather it is caused by variance increase in order amounts of the retailer nodes. For $product_1$, all values regarding absolute order variances of distributor and retailer echelons are greater in the case where preventive ordering is used (see Figure 3.8). However for $product_2$, when information is shared with both echelons, order variances of distributor echelon decline for FDIS and HDIS with preventive ordering (see Figure 3.9). This outcome is related to the combined effect of two factors which are high service levels of both distributor and retailer echelons and elimination of zero order amounts due to shortage amounts emanate in the beginning and end of the optimization horizon.

Product based comparisons regarding bullwhip effect present interesting results. When preventive ordering is excluded, bullwhip effect on distributor echelon for $product_1$ is greater for all IS strategies except FDIS with both echelons. Since order amounts of retailer echelon is independent from the IS strategies, bullwhip effect almost remains constant for all IS strategies. When preventive ordering is included, bullwhip effect on distributor echelon for $product_1$ is greater for all IS strategies except IS with only distributor echelon and HDIS with both echelons. This outcome is closely related with service levels of the distributors. When IS with distributor echelon is ongoing, service level of distributor echelon for $product_1$ is greater due to certain reasons explained before. Therefore shortages occur less frequently

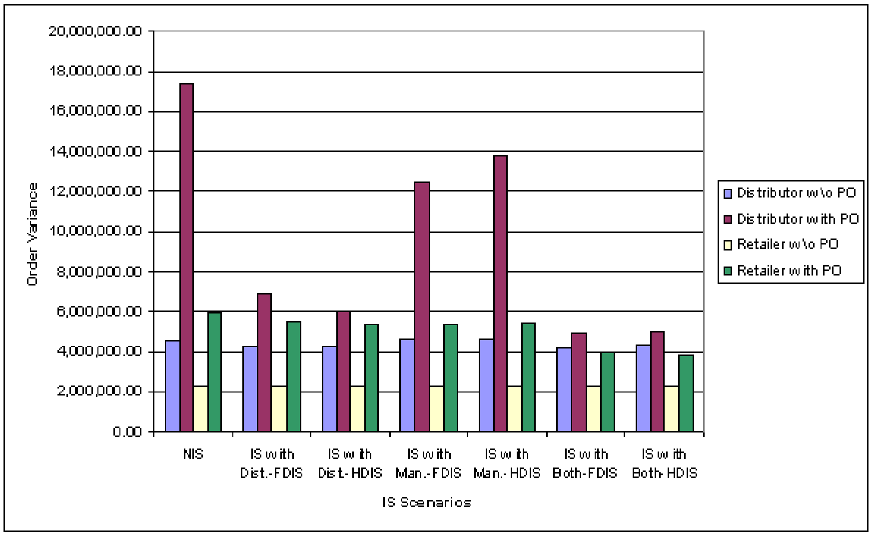

Figure 3.8: Order Variances of Distributor and Retailer echelons for $Product_1$

for $product_1$ leading to less number of preventive orders. On the other hand, bullwhip effect on retailer echelon for $product_1$ is greater for all IS strategies except NIS. Due to shorter lead time required to get $product_2$, exaggerated orders of retailer for this product are satisfied more easily than the orders for $product_1$. Therefore maximum inventory level for $product_2$ is greater and this leads to higher order variance. Shortages for $product_1$ oscillate in a narrower band since the preventive orders for this product are almost never fully satisfied. When there is any kind of IS, preventive order amounts decrease hence bullwhip effect also decreases. Because of the shorter lead time required to get $product_2$, orders and shortages are more stable compared to $product_1$ hence bullwhip effect for $product_2$ is always less than bullwhip effect for $product_1$.

Table 3.9: Bullwhip Effect on Distributor and Retailer Echelons with Preventive Ordering

		Distributor		*Retailer*	
	IS Schemes	$Product_1$	$Product_2$	$Product_1$	$Product_2$
	NIS	2.93	2.39	3.38	4.36
IS with Distributor Echelon	**FDIS**	1.26	1.65	3.14	1.83
	HDIS	1.13	1.63	3.06	1.99
IS with Manufacturers	**FDIS**	2.33	1.80	3.07	1.81
	HDIS	2.54	1.55	3.10	2.22
IS with Both Echelons	**FDIS**	1.24	1.15	2.27	1.46
	HDIS	1.30	1.32	2.20	1.51

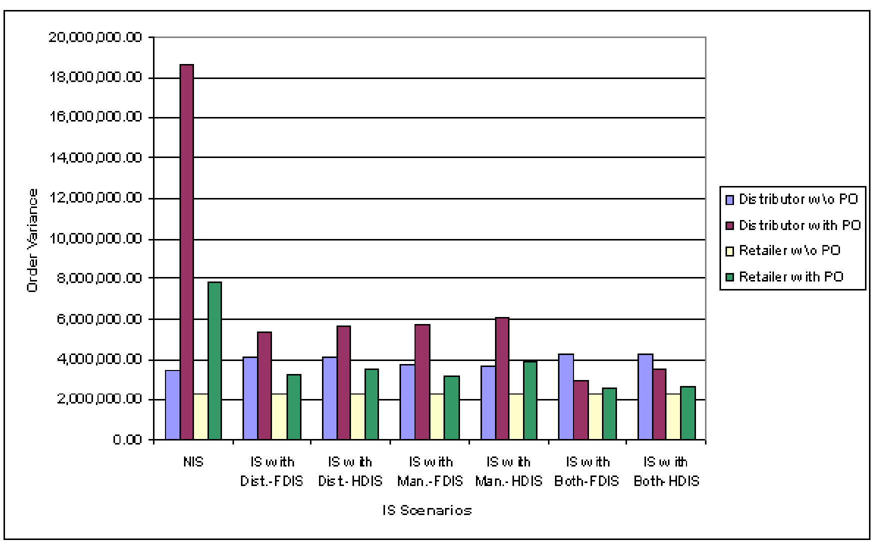

Figure 3.9: Order Variances of Distributor and Retailer echelons for $Product_2$

Chapter 4

HORIZONTAL UPSTREAM COMPETITION IN DECENTRALIZED SUPPLY CHAIN SYSTEMS

In this chapter, horizontal competition of manufacturer nodes in a supply chain system similar to the one in the previous chapter is analyzed. First, the setting in which competition is considered, together with the related assumptions, are introduced. Then, theoretical game theory framework used in this study is presented that covers the associated methodology and assumptions. Finally, analysis of numerical applications of the various game theoretic approaches with different scenarios is presented.

4.1 Competition Setting

The particular supply chain system and its operation in this chapter is almost the same as the one in chapter 3. The main difference between the systems is substitutability of products of different manufacturers. At the beginning of the optimization horizon, manufacturers face the decision of choosing a profit margin/quality scheme which cannot be changed once optimization horizon starts. This decision is similar to the one that has to be made in the previous chapter (IS Scheme selection) and can also be thought as a strategic decision. After manufacturers announce their profit margin/quality scheme (PQS), their market shares are specified with an explicit market share function. Naturally, retailers favor high quality and low price products when trading with distributors and market share function is designed to reflect this behavior (see equation 4.1).

$$M_{i'} = \frac{\frac{Q_{i'}}{P_{i'}} \prod\limits_{i \neq i'} \frac{P_i}{Q_i}}{\sum\limits_{i} \left[\frac{Q_i}{P_i} \prod\limits_{\hat{i} \neq i} \frac{P_{\hat{i}}}{Q_{\hat{i}}} \right]} \qquad \forall i' \in I \ , \tag{4.1}$$

where M_i' is the market share of manufacturer i' and Q_i and P_i represents the quality level and the sales price, respectively. In order to clarify, Q_i is a quantifiable dimension of quality such as reliability(life span) or mean defect ratio such as parts per million. Demand in an arbitrary period for a product at the retailer echelon (in anticipation of customer demand) is determined by multiplying the total forecasted customer demand in that period with the market share of the particular manufacturer that produces the corresponding product.

A PQS also contains production yield of the manufacturers. A PQS with high quality provides high production yield. Production yield can be defined as the net production amount after scrapes or defected products are removed from a batch. The optimization approach (MILP, RHPC) is the same as the one adopted in the previous chapter except that a new set L: set of PQS Schemes, is included and parameters rm_i, v_i and y_i are changed as $rm_{i,l}$, $v_{i,l}$ and $y_{i,l}$ ($rm_{i,l}$ denotes sales price of manufacturer i under PQS l $i.e$). Also a new parameter, $quality_{i,l}$ is added to the model in order to denote the quality level. These parameters are the same for different manufacturers ($rm_{1,2} = rm_{2,2}$ $i.e$). There are some changes in objective functions and constraints and those changes can be found in Appendix.

4.2 Game Theoretic Approach

Existing examples related to applications of game theoretic approaches in supply chain analysis were presented in Section 2.3. Similar approaches are used also in this study therefore subsections belonging to this section are devoted to give important insight about assumptions behind game theory, different types of games and solution methodologies for these games. Basically, game theory involves the framework with the aim of understanding the way informed individuals make choices when actions taken by different players affect actions of at least one other player (see Romp [1997]). The assumptions related to the definition above is presented in the following section.

4.2.1 Fundamental Assumptions of Game Theory

In game theory, individuals are assumed to be rational decision makers and they always try to achieve best consequences for their own interest while making choices. In the cases when players can not exactly know the outcome of an action at least they are informed of the probability of such an outcome. This assumption is questionable as all assumptions since there is a high probability of being not completely rational when making a decision regarding a significantly complex problem. However, the main justification of this assumption is the possible convergence of all individuals to full rationality if they had the ability to do so.

Therefore even if complex situations such as the one in this study is to be modeled with game theory, rationalism assumption is the key for understanding the behavior of decision makers.

Another assumption regarding game theory is mutual interdependence. When interdependence assumption is excluded, an action taken by a player does not affect other players. This assumption also maintains Pareto efficiency that means a player can not obtain a better outcome without making another player end up with a worse outcome. However with interdependency, Pareto efficiency is not guaranteed (Romp [1997]). Interdependency assumption is valid for this study, since manufacturers try to capture maximum profit by selling substitutable products to a fixed sized market.

4.2.2 Game Types

Games can be grouped into two main parts; non-cooperative and cooperative games, respectively. As the names suggest, non-cooperative games represent the situations where players can not make deals with one another. Conversely, cooperative games do not prohibit to do so. In this study, both type of games are included for analysis.

Level of true, accessible information utilized by different players while making decisions specifies the information aspect of the games. If all players are fully aware of the parameters and outcomes related to those parameters in a decision making process, the game is called as a full information game. Otherwise, the game is called as an asymmetric information game. The game context in study excludes asymmetric information. Therefore all players know the exact values of the parameters and related outcomes. Full information also means that manufacturers have access to historic demand data otherwise they could not be able to make decisions before optimization horizon starts. They also know the forecast parameters of the retailer node and by plugging historic demand data to the forecast model of the retailer they can have access to forecasts of the retailer. Using historic demand data with an ARMA model or Winter's seasonal forecasting method is another decision for manufacturers but in the previous chapter, using an ARMA model performed better than forecasting method of the retailer did for both manufacturers when demand information is shared with manufacturers only (see Table 3.3). Hence that decision is omitted and manufacturers use ARMA models.

Number of stages in which players can make decisions also determines the type of the game. Games can be static; all players announce their decisions simultaneously, or dynamic; different players may announce their decisions at different time points (Cachon and Netessine [2004]). For instance, Stackelberg game is a sequential dynamic game, in which a leader has the power to announce his decision first and based on his decision a follower makes a decision with the aim of achieving the best outcome for himself (Von Stackelberg [1934]). The leader has the advantage of dictating the best policy to his followers in anticipation of their decisions. In this study, the game between manufacturers is a static game so they have to decide on their PQS concurrently. However while a manufacturer is determining best possible outcome based on his and his competitor's actions, he act as a Stackelberg leader in his relationship with the retailer by having the ability to choose and dictate a PQS in anticipation of the decision of retailer.

A special type of cooperative games is included in this study and called bi-form game. A Bi-form game is a cooperative game obtained from a non-cooperative game (Brandenburger and Stuart [2000]). In this study for instance, in the case of three competing manufacturers, first equilibrium strategies are identified in a non-cooperative static game. Then manufacturers threaten their competitors by choosing a strategy that worsens other players off while making himself unchanged, better off or even worse off. If there is a player with more dominant threats than threats of all remaining players, a consensus is formed meeting his demands otherwise players stick to initial equilibrium conditions. In the threatening case, it is assumed that players will realize their threats for certain if their demands are not met.

4.2.3 Solution Approaches

In this study NE solutions are accepted as the outcomes of manufacturer competition. In a NE solution, none of the players can achieve a better outcome by altering only their decisions (Nash [1950]). However in the case of a NE solution, a better solution for all players may exist.

NE solutions exist if best responses (best decision that should be made for a given set of decisions of the competitors) of all players have at least one common strategy combination. There can be more than one common strategy combinations and in that case, if there exists a solution among possible NE solutions that dominates all other NE solutions for all players, players will converge to that solution. Obtaining a NE solution in a non-cooperative static game is presented below:

dec_i: decision of manufacturer i

E_i: feasible decision set of manufacturer i

CE_{i-}: cartesian product of feasible decision set of manufacturers excluding manufacturer i

$\pi_i(dec_1, ..., dec_i, ..., dec_I)$: utility of manufacturer i if he chose dec_i and his competitors chose $(dec_1, ..., dec_{i-1}, dec_{i+1}, ..., dec_I)$

$BR_{i(i')}$: best response of manufacturer i for $i'th$ competitor decision combination

BR_i: best response set of manufacturer i

Definition 1. *Let* $C = (dec_1, ..., dec_{i-1}, dec_i^*, dec_{i+1}, ..., dec_I)$ *be a decision combination where* $(dec_1, ..., dec_{i-1}, dec_{i+1}, ..., dec_I)$ *is the* $i'th$ *competitor decision combination for manufacturer* i*.* C *is a best response* $BR_{i(i')}$ *if* $dec_i^* = \underset{dec_i \in E_i}{argmax}\, \pi(dec_1, ..., dec_{i-1}, dec_i, dec_{i+1}, ..., dec_I)$ *and* $BR_i = \bigcup_{\hat{i} \in CE_{i-}} BR_{i(\hat{i})} \quad \forall i$*.*

Definition 2. *If there exists a decision combination* $A = (dec_1^*, ..., dec_{i-1}^*, dec_i^*, dec_{i+1}^*, ..., dec_I^*)$: $A \in BR_i \quad \forall i$*, then* A *is a NE solution.*

For a detailed study related to theory and applications of game theory in supply chain systems see Cachon and Netessine [2004].

4.3 Numerical Analysis

In this section, two different feasible PQS s are considered for two competing manufacturers together with their individual and comparative analysis of the impact on different decision makers. Individual manufacturers differ in transportation attributes as they do in the previous chapter and all transportation parameters regarding manufacturers are the same. A generalized form of the market share function is introduced and the impact of price and quality sensitivity of the retailers on different decision makers is discussed. Price and quality elasticity of customer demand are incorporated to the decision making process of the retailer and related consequences are discussed for both cases in which basic or generalized market share functions are used. Finally competition between three manufacturers is analyzed. One unique and one multiple equilibria situations are shown and an alternative solution method is introduced. A bi-form game is formed with the threat option stated in Section 4.2.2 and corresponding solution and resulting effects on different decision makers are discussed.

4.3.1 PQS Schemes and Results

In the first feasible PQS set, profit margin and quality (production yield) are assumed to be positively correlated and shown in Table 4.1. Revenues and variable costs are monetary amounts. Production yield presents the net production out of one unit raw material. Quality can be lifespan of the products in months. Hybrid selections can not be made. For instance if PQS_1 is selected, revenue, variable cost, production yield and quality level must strictly be 250, 50, 0.75 and 7.5, respectively.

Table 4.1: First Feasible PQS Set

	PQS_1	PQS_2	PQS_3
Sales Price	250	275	300
Variable Cost	50	60	70
Production Yield	0.75	0.85	0.95
Quality Level ($quality_{i,l}$)	7.5	8.5	9.5

Resulting NE equilibrium profits are shown in Table 4.2. Profits are scaled based on the minimum value in the table and individual cells represent $profitmanufacturer_{1,lr}$; $profitmanufacturer_{2,lc}$ where indexes lr and lc are the PQS s in corresponding rows and columns.

Table 4.2: NE (Profit) for the first Feasible PQS Set

$Manufacturer_1/Manufacturer_2$	PQS_1	PQS_2	PQS_3
PQS_1	2.559;1.075	2.485;1.768	2.426;2.479
PQS_2	3.275;1.034	3.182;1.710	3.108;2.405
PQS_3	4.019;1.000	3.909;1.658	**3.819;2.341**

There is a unique NE solution ($PQS_3; PQS_3$) which also Pareto optimal since it yield highest total profit. Both manufacturers face competition penalties (difference between the profit for NE solution and maximum achievable profit). If $manufacturer_1$ had power over $manufacturer_2$, he would force him to select PQS_1 and if the opposite were true $manufacturer_2$ would force $manufacturer_1$ to select PQS_1. Table 4.3 explains this situation.

Table 4.3: NE (Market Share) for the first Feasible PQS Set

$Manufacturer_1/Manufacturer_2$	PQS_1	PQS_2	PQS_3
PQS_1	0.500;0.500	0.485;0.515	0.473;0.527
PQS_2	0.515;0.485	0.500;0.500	0.488;0.512
PQS_3	0.527;0.473	0.512;0.488	**0.500;0.500**

A manufacturer obtains the maximum market share when he selects PQS_3 and his competitor selects PQS_1. This is due to the difference in relative changes if price and quality level. For instance, if $manufacturer_1$ selects PQS_3 and $manufacturer_2$ selects PQS_1, market share of $manufacturer_1$ is maximum because relative positive effect of quality on market share dominates relative negative effect of price. Eventually, highest profit margin and highest market share make $(PQS_3; PQS_1)$ most favorable situation for both manufacturers but since no manufacturer has any power on the other one, NE equilibrium is $(PQS_3; PQS_3)$. Furthermore, NE equilibrium for market share competition is also same.

The case in which price and quality are inversely proportional is presented in Table 4.4.

Table 4.4: Second Feasible PQS Set

	PQS_1	PQS_2	PQS_3
Sales Price	300	275	250
Variable Cost	50	60	70
Production Yield	0.75	0.85	0.95
Quality Level ($quality_{i,l}$)	7.5	8.5	9.5

In this case, manufacturers act more aggressively to capture higher market shares. NE equilibrium for this case is shown in Table 4.5.

Table 4.5: NE (Profit) for the second Feasible PQS Set

$Manufacturer_1/Manufacturer_2$	PQS_1	PQS_2	PQS_3
PQS_1	3.405;2.075	2.707;2.082	2.111;1.610
PQS_2	**3.435;1.588**	2.864;1.539	2.296;1.405
PQS_3	3.160;1.210	2.754;1.168	2.334;1.000

Resulting NE solution is a compromise between price and market share. Different PQS s have greater impacts on the market shares since moving towards PQS_1 from PQS_3 creates a decline in market share larger than the one for the first feasible PQS set. Therefore NE solution is the balance between decreasing market share and increasing profit margin. In this solution $manufacturer_1$ do not face a competition penalty whereas $manufacturer_2$ obtains less profit than his potential maximum: $(PQS_1; PQS_2)$. In addition NE and centralized (Pareto) solutions are different because $(PQS_1; PQS_1)$ yields maximum total profit.

NE solution for market shares is shown in Table 4.6. The result is intuitive since moving towards PQS_3 positively affects market share by means of low price and high quality.

Table 4.6: NE (Market Share) for the second Feasible PQS Set

$Manufacturer_1/Manufacturer_2$	PQS_1	PQS_2	PQS_3
PQS_1	0.500;0.500	0.395;0.605	0.302;0.698
PQS_2	0.605;0.395	0.500;0.500	0.398;0.602
PQS_3	0.698;0.302	0.602;0.398	**0.500;0.500**

4.3.2 Price and Quality Elasticity of Customer Demand

Today, in most of the retailing environments customer demand is mainly driven by sales price. However quality of the product can be a major factor as well as price, affecting customer demand. In this section, incorporation of price and quality elasticty is modeled and analyzed via numerical scenarios. Intuitively, similar to the rationing of retailer orders for different products, customer demand is negatively correlated with price and positively correlated with quality. In the case where there was no price elasticity of customer demand, retailer nodes add a fixed margin to the purchasing price they pay to distributor nodes. However, now they have the ability to optimally adjust the price. While determining their sales price, retailers must also take the sales price of manufacturers since it constitutes the major portion of the purchasing price that retailers pay to distributors. Quality on the hand is directly under control of the manufacturers because as Stackelberg leaders, they announce their PQS decisions first and such would be the case in a duopoly like the one in this study. It is assumed that manufacturers know price and quality elasticity of customer demand otherwise the game would be an asymmetric information game. Before announcing a PQS, manufacturers know the optimal sales price of the retailers for the PQS they will choose. Combining that sales price information with the quality level in the PQS they will choose, they can adjust the historic demand data according to the price and quality flexibilities and determine his and his competitor's profit so that NE solution can be found if existing.

Under price and quality elasticity of customer demand, retailer nodes face a nonlinear unconstrained optimization problem for determining optimal sales price. Additional parameters, variables and objective function of the retailer nodes is given below:

Parameters of Retailer Nodes:

$pelasticity_k$: price elasticity

$qelasticty_k$: quality elasticity

$histdemand_{k,t}$: historic demand

$baseprice_k$: base price level

Decision Variables of Retailer Nodes:

$price_{p,k,l}$: sales price

Objective function for Retailer Nodes:

$$\max \quad profitretailerflex(price_{p,k,l}) = \sum_{i=p}\sum_{t}\Big(M_i histdemand_{k,t}\Big)\Big(1 - \frac{price_{p,k,l} - baseprice_k}{baseprice_k} pelasticity_k + \frac{\sum_{i=p} quality_{i,l} - \min_{l \in L, i=p} quality_{i,l}}{\min_{l \in L, i=p} quality_{i,l}} qelasticity_k\Big) (price_{p,k,l} - \sum_{i=p}\sum_{j}(dmargin_{p,j} + rm_{i,l}) quota_{j,k}) \qquad \forall p,k,l \ . \tag{4.2}$$

The profit function in equation 4.2 is a simple concave function hence its unique optimal solution can be obtained via differentiating and solving for $\frac{d\ profitretailerflex(price_{p,k,l})}{d\ price_{p,k,l}} = 0$ yields optimal price: $price^*_{p,k,l}$. In anticipation of this optimization, $manufacturer_i$ adjusts historic demand data for his product for optimal retailer $price^*_{p,k,l}$ by equation 4.3

$$histdemandman_{i,l,k,t} = M_i histdemand_{k,t}\Big(1 - \frac{\sum_{p=i} price^*_{p,k,l} - baseprice_k}{baseprice_k} pelasticity_k + \frac{quality_{i,l} - \min_{l \in L} quality_{i,l}}{\min_{l \in L} quality_{i,l}} qelasticity_k\Big) \qquad \forall i,l,k,t \ , \tag{4.3}$$

where $histdemandman_{i,l,k,t}$ is the adjusted historic demand for the product of $manufacturer_i$ under PQS l at retailer k and in period t.

NE solution for manufacturer competition based on profits is shown in Table 4.7. Profits are obtained for the first feasible PQS set (see Table 4.1).

Table 4.7: NE (Profit) for the first Feasible PQS Set under Price and Quality Elasticity

$Manufacturer_1/Manufacturer_2$	PQS_1	PQS_2	PQS_3
PQS_1	2.751;1.075	2.704;1.890	2.631;2.842
PQS_2	3.768;1.020	3.701;1.835	3.610;2.753
PQS_3	4.728;1.000	4.723;1.787	**4.505;2.684**

NE solution is $(PQS_3; PQS_3)$ meaning that high sales price of the manufacturer do not force retailer echelon to set substantially high sales prices making customer demand shrink.

In this case Pareto optimal solution is same as the NE solution despite both manufacturers face competition penalty. NE solution under price and quality elasticity for the second feasible PQS set is shown in Table 4.8.

Table 4.8: NE (Profit) for the second Feasible PQS Set under Price and Quality Elasticity

$Manufacturer_1/Manufacturer_2$	PQS_1	PQS_2	PQS_3
PQS_1	2.612;1.684	2.097;1.972	1.586;2.266
PQS_2	3.874;1.386	3.241;1.626	2.322;1.680
PQS_3	4.453;1.000	3.875;1.299	**3.242;1.334**

In this case, NE solution is again $(PQS_3; PQS_3)$. Like the previous result in Table 4.7 both manufacturers end up with competition penalties and Pareto optimal solution is different from NE solution and is $(PQS_3; PQS_1)$. However, the most interesting part of this case is the existence of a solution which makes both manufacturers better off: $(PQS_2; PQS_1)$. But since the game is organized as a non-cooperative game, players do not commit themselves to that solution because they cannot make agreements prior to the announcement of their decisions. Eventually, in the absence of such an agreement, players act in their self interests trying to maximize their own profits.

Figure 4.1 exhibit profits of all decision makers based on NE solution for different feasible PQS sets and elasticity features. Most significant result is the increase in the profit of the retailer echelon. This means that if sales price of the retailer is set by adding a fixed margin to the purchasing price paid to the distributor echelon, corresponding sales price is too below the optimal price level. However incorporation of price and quality flexility results in decreases for both manufacturers and distributor echelon, for both PQS sets. For the first feasible PQS set, NE solutions for manufacturer competition were the same whether there was price and quality elasticity or not. Therefore the reductions in the profits of manufacturers and distributor echelon is caused by decline in customer demand due to pricing of retailer echelon. On the other hand, incorporation of price and quality elasticity alters NE solution to $(PQS_3; PQS_3)$ from $(PQS_2; PQS_1)$ when second feasible PQS set is used. Consequently, the cause behind the decline in the profit level of the manufacturers is a combination of three factors which are lower sales price, non-cooperative behavior of the manufacturers and less demand caused by independent pricing of the retailer while the decline in the profit level of the distributor echelon is again mainly due to the reduction in the customer demand because even if the NE solution changes distributor earns same unit profit from a single unit sold. Lastly, both the absolute increase in the profit level of the retailer echelon and the absolute decrease in the profit levels of the manufacturers and distributor echelon is greater if price and quality elasticity is incorporated when second PQS set is eligible. This quite intuitive because the change in NE solution increases quality level of the manufacturers and retailer utilizes the advantage of achieving high quality resulting in greater market demand without making any sacrifices in the process.

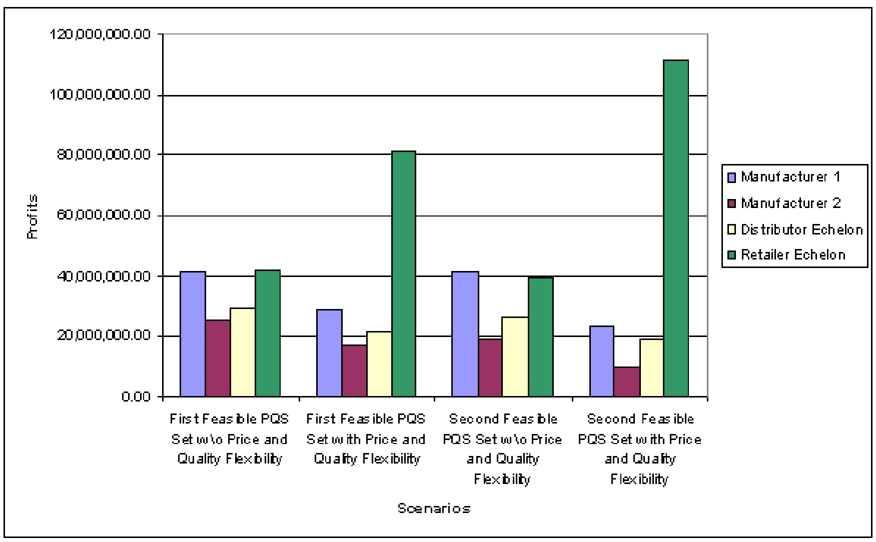

Figure 4.1: NE Profits for Different Decision Makers

4.3.3 Generalized form of the Market Share Function

Equation 4.1 in Section 4.1, gives equal weights to price and quality sensitivities of the retailer echelon. However there may be cases this denying this assumption. These weights can be incorporated via addition of exponential parameters into the market share function. Such a modification is shown in equation 4.4.

$$M_{i'} = \frac{\frac{Q_{i'}^a}{P_{i'}^b} \prod_{i \neq i'} \frac{P_i^b}{Q_i^a}}{\sum_i \left[\frac{Q_i^a}{P_i^b} \prod_{\hat{i} \neq i} \frac{P_{\hat{i}}^b}{Q_{\hat{i}}^a} \right]} \qquad \forall i' \in I \ , \tag{4.4}$$

where a and b are the exponential weights associated with quality level and sales price adopted by the manufacturers and used by the retailer echelon when he rations his orders out to the distributors. Effects of increasing price sensitivity of retailer echelon on manufacturers while keeping quality sensitivity at 1 ($a = 1$), are analyzed for the first feasible PQS set since price is positively correlated with quality level. The relationship between the price sensitivity of the retailer echelon and the competition penalty the manufacturers end up with, is shown in Figure 4.2.

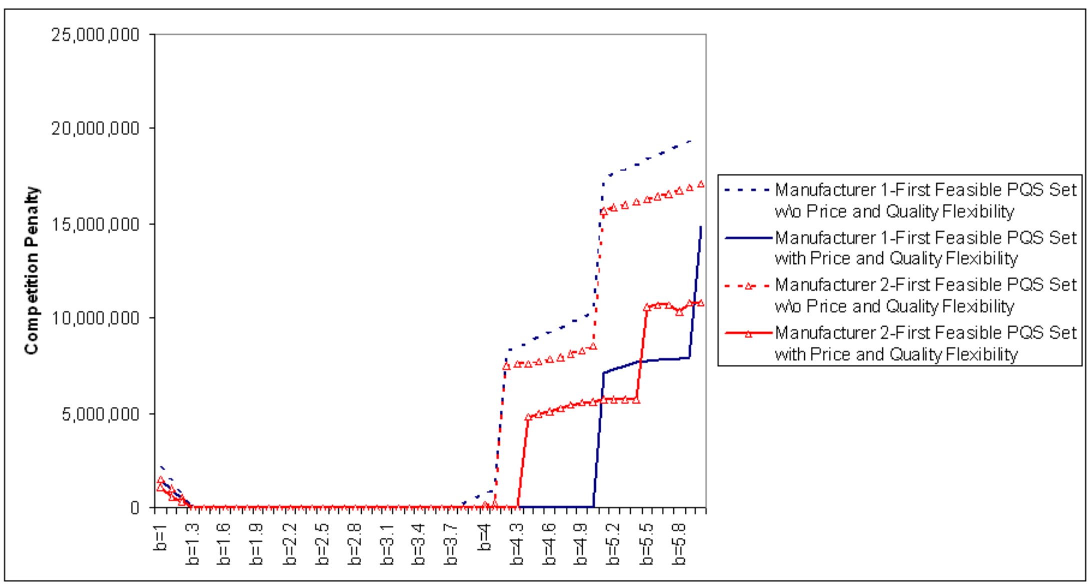

Figure 4.2: Competition Penalties for different values of b

Initially all scenarios decrease in competition penalty because price sensitivity is not high enough to suppress high sales prices of the manufacturers. Then NE equilibrium profits and maximum achievable remains equal to each other until b is greater than 4. When b is around 4.2 NE solutions for all scenarios shift depicted as jumps in the figure. Afterwards competition penalties steadily increase again making jumps at the points where NE solution changes. As b increases, high prices favored by the manufacturers are penalized by the decrease in market share eventually altering the NE solution. When price and quality elasticity of the customer demand is not included, $manufacturer_1$ always faces greater competition penalty. On the hand, for the incorporation of price and quality elasticity same statement can not be made.

In order to analyze the effects of quality sensitivity of retailer echelon, second feasible PQS set is used. This time, under negative correlation of sales price and quality level, manufacturers again chase high sales prices more than high quality levels hence it is convenient to use the second feasible PQS set in this analysis. The relationship between the quality sensitivity of the retailer echelon and the competition penalty the manufacturers end up with when b is fixed to 1, is shown in Figure 4.3.

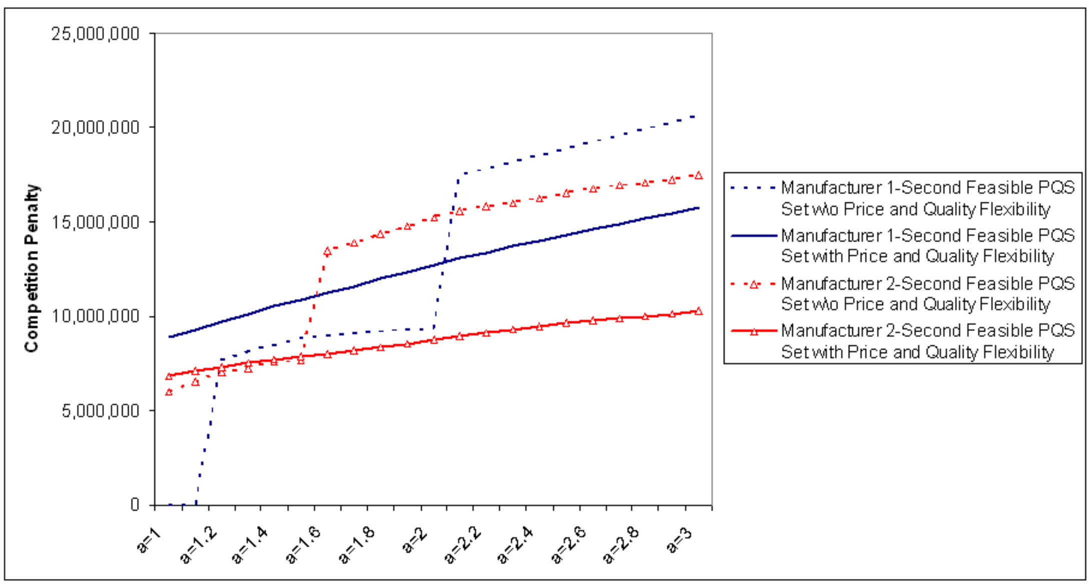

Figure 4.3: Competition Penalties for different values of a

Similarly to the previous case, manufacturer's tendency to select higher sales prices is penalized by the high importance given to quality by retailer echelon. Therefore competition penalties increase constantly, making jumps in the equilibrium changes. In this case, the curve of competition penalty of $manufacturer_1$ is above the one belonging to $manufacturer_2$ if price and quality elasticity of customer demand is included. Exclusion of price and quality elasticity eliminates such a relationship.

4.3.4 Three Manufacturers Case

The case in which three non-cooperative manufacturers compete is also analyzed. NE solutions are found by the methodology presented in Section 4.2.3. The graphical interpretation of that methodology suggests searching for the intersection of best response curves (functions) in order to capture the point on which best response curves of all players are equal. Transportation parameters of the manufacturers are shown in Table 4.9.

Table 4.9: Manufacturer Parameters

Parameter	$Manufacturer_1$	$Manufacturer_2$	$Manufacturer_3$
Transportation Lead Time	3	2	1
Transportation Capacity	14000	12000	10000
Average Transportation Cost	8	13	18

Second feasible PQS set is used with parameters having same values and the visualization of the NE solution is depicted in Figure 4.4. The values on the axes denote PQS numbers and lines in different forms (color, line style etc.) denote best response functions. NE solution is the intersection of the best response functions and there is a unique NE solution which is $(PQS_3; PQS_3; PQS_2)$.

Second feasible PQS set is modified in order to illustrate a multiple equilibria case. Modified version of the second feasible PQS set is shown in Table 4.10. The only alteration is in the feasible price choices. The absolute difference in the subsequent price choices is increased. Resulting NE can be found in Figure 4.5.

In this case there are two NE solutions which are $(PQS_2; PQS_2; PQS_1)$ and $(PQS_3; PQS_3; PQS_2)$. In such cases, rational players would search for better equilibrium points meaning a solution dominates other ones for all players. Comparison of two equilibria shows that $(PQS_2; PQS_2; PQS_1)$ yield higher profits for all manufacturers than $(PQS_3; PQS_3; PQS_2)$ does (see Table 4.11). Therefore manufacturers are expected to be simultaneously announcing PQS_2, PQS_2 and PQS_1, respectively if the situation is considered within non-cooperative game theory framework.

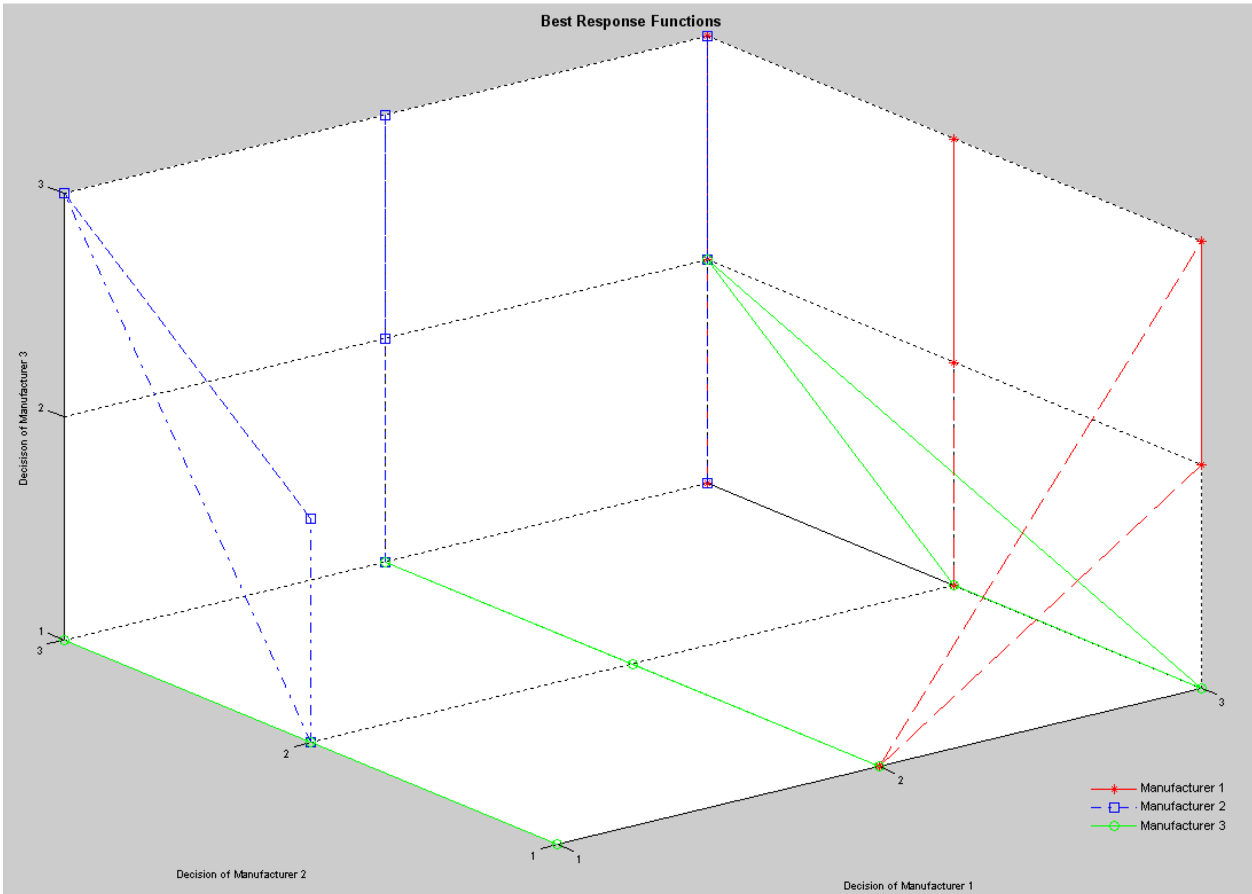

Figure 4.4: NE (profit) for the second feasible PQS set-3 Manufacturers

4.3.5 Bi-form Game for Three Manufacturers Case

A bi-form game is organized for the three supplier case in the following manner. Initially the game is carried out as a non-cooperative, static and full information game. According to the resulting profits of different PQS decision combinations of the manufacturers and based on the NE solution each manufacturer makes a threat to other manufacturers separately so that a threatened manufacturer knows the content of the threats which are either directed by him or to him. In addition, an enforcing agreement between manufacturers assumed to be existing which guarantees a threat is carried out by the threatening party for certain. Due to these attributes, second phase of the game is a cooperative and asymmetric information game. In the second phase of the game, a manufacturer individually threats his competitors

Table 4.10: Second Feasible PQS Set (Modified)

	PQS_1	PQS_2	PQS_3
Revenue	350	300	250
Variable Cost	50	60	70
Production Yield	0.75	0.85	0.95
Quality Level ($quality_{i,l}$)	7.5	8.5	9.5

Table 4.11: Comparison of Multiple Equilibria in terms of Profits

	$Manufacturer_1$	$Manufacturer_2$	$Manufacturer_3$
$(PQS_2; PQS_2; PQS_1)$	4.264	3.735	2.224
$(PQS_3; PQS_3; PQS_2)$	2.907	2.327	1.427

by choosing the PQS that minimizes his maximum achievable profit. If a manufacturer's threat dominates the counter threats of other manufacturers, PQS s are selected in the way dominating manufacturer desires. A numerical example is constituted for the first feasible PQS set. Firstly, NE solution is determined and it was $(PQS_3; PQS_3;\ PQS_3)$. Profits for all possible PQS decision combinations are shown in Table 4.12.

Each manufacturer directs a threat to each and every manufacturer separately. The threat consists of the PQS that threatening party wants to make threatened party select and PQS that threatening party will select if threatened party ignores the threat. According to the profits in Table 4.12 resulting threats are formed by corresponding manufacturers and are shown in Tables 4.13 4.14. Exponential values over PQS s show the maximum achievable profits under corresponding selection of either threatened or threatening player.

Tables 4.13 and 4.14 suggest that none of the manufacturers directs a threat that can not be ignored since all of values in Table 4.14 are greater than the values in Table 4.13 meaning that the consequences that would be faced by any manufacturer are better if corresponding threats are ignored. Eventually, second phase of the game do not yield any agreement hence manufacturers do not switch from NE solution obtained in the first phase.

Same bi-form game is conducted for the second (not modified) feasible PQS Set. NE solution: $(PQS_3; PQS_3; PQS_2)$ as well as profits for all possible PQS decision combinations

Table 4.12: Possible Profit Levels for all PQS Decision Combinations (First Feasible PQS Set)

PQS Combinations	$Manufacturer_1$	$Manufacturer_2$	$Manufacturer_3$
$(PQS_1; PQS_1; PQS_1)$	2.7583	1.8133	1.0657
$(PQS_1; PQS_1; PQS_2)$	2.7027	1.7725	1.7733
$(PQS_1; PQS_1; PQS_3)$	2.6568	1.7376	2.5200
$(PQS_1; PQS_2; PQS_1)$	2.7027	2.5697	1.0387
$(PQS_1; PQS_2; PQS_2)$	2.6492	2.5185	1.7391
$(PQS_1; PQS_2; PQS_3)$	2.6051	2.4818	2.4680
$(PQS_1; PQS_3; PQS_1)$	2.6568	3.3482	1.0210
$(PQS_1; PQS_3; PQS_2)$	2.6051	3.2822	1.7122
$(PQS_1; PQS_3; PQS_3)$	2.5625	3.2277	2.4281
$(PQS_2; PQS_1; PQS_1)$	3.5290	1.7725	1.0387
$(PQS_2; PQS_1; PQS_2)$	3.4653	1.7319	1.7391
$(PQS_2; PQS_1; PQS_3)$	3.4109	1.6983	2.4680
$(PQS_2; PQS_2; PQS_1)$	3.4653	2.5185	1.0154
$(PQS_2; PQS_2; PQS_2)$	3.4415	2.4747	1.7155
$(PQS_2; PQS_2; PQS_3)$	3.3847	2.4335	2.4212
$(PQS_2; PQS_3; PQS_1)$	3.4109	3.2822	1.0006
$(PQS_2; PQS_3; PQS_2)$	3.3847	3.2187	1.6788
$(PQS_2; PQS_3; PQS_3)$	3.3297	3.1683	2.3852
$(PQS_3; PQS_1; PQS_1)$	4.3496	1.7376	1.0210
$(PQS_3; PQS_1; PQS_2)$	4.2719	1.6983	1.7122
$(PQS_3; PQS_1; PQS_3)$	4.2076	1.6737	2.4281
$(PQS_3; PQS_2; PQS_1)$	4.2719	2.4818	1.0006
$(PQS_3; PQS_2; PQS_2)$	4.1970	2.4335	1.6788
$(PQS_3; PQS_2; PQS_3)$	4.1351	2.3922	2.3852
$(PQS_3; PQS_3; PQS_1)$	4.2076	3.2277	1.0000
$(PQS_3; PQS_3; PQS_2)$	4.1351	3.1683	1.6515
$(PQS_3; PQS_3; PQS_3)$	**4.0714**	**3.1236**	**2.3496**

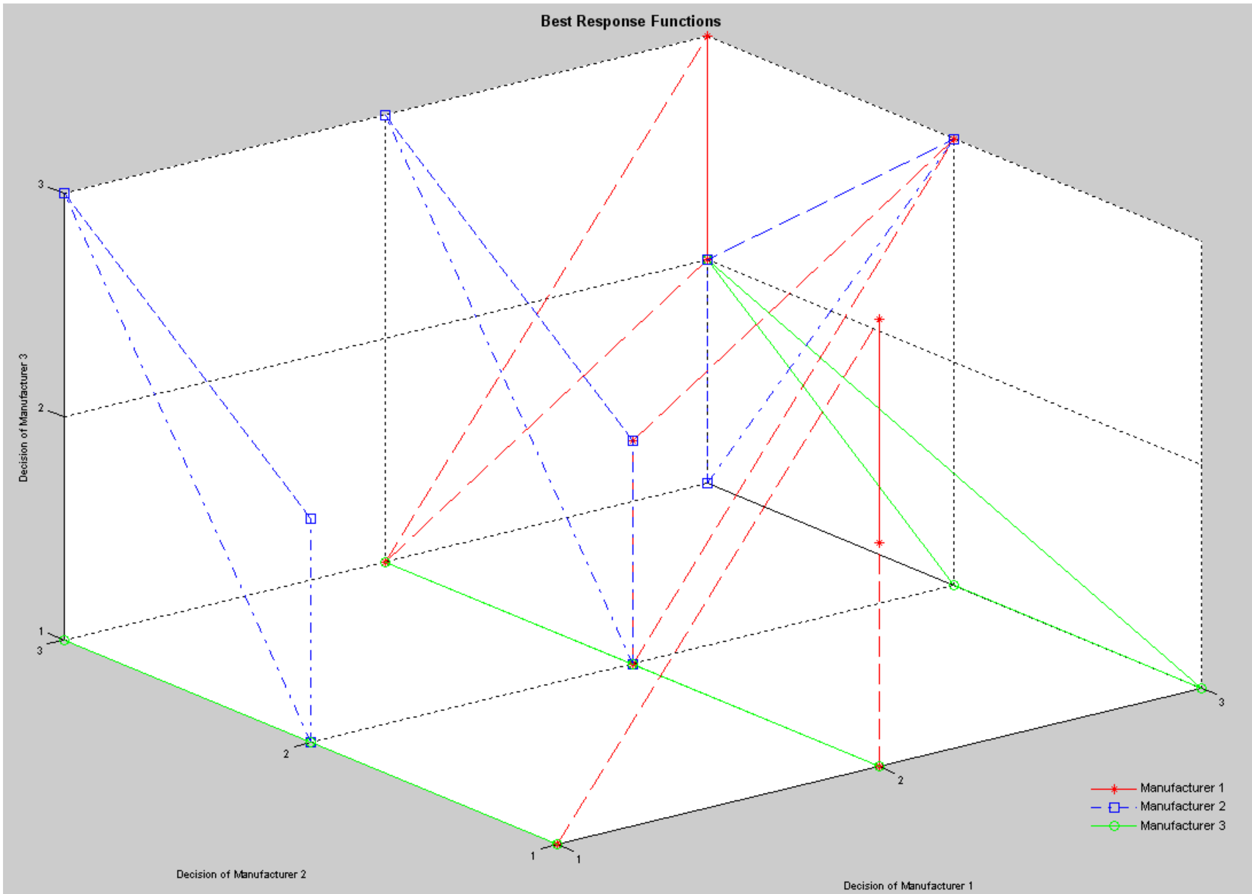

Figure 4.5: NE (profit) for the second (modified) feasible PQS set-3 Manufacturers

are shown in table 4.15.

According to the profits in Table 4.15 resulting threats are formed by corresponding manufacturers and are shown in Tables 4.16 and 4.17.

Since all of values in Table 4.17 are less than the values in Table 4.16, manufacturers face potential loses by ignoring the threats directed to them. Therefore threat comparison can be performed. The potential decline in the maximum achievable profit of a manufacturer is simply the difference between values in Tables 4.16 and 4.17. These differences are shown in Table 5.14.

From Table 5.14 it can be seen that threat of $manufacturer_1$ is dominated by threats of both $manufacturer_2$ and $manufacturer_3$. Furthermore threat of $manufacturer_3$ is dominated by threat of $manufacturer_2$. Even if threat of $manufacturer_2$ is imposes a greater

Table 4.13: Desired PQS s from Competitors and Maximum Achievable Profits

Threatening/Threatened	$Manufacturer_1$	$Manufacturer_2$	$Manufacturer_3$
$Manufacturer_1$	N/A	$PQS_1^{1.8133}$	$PQS_1^{1.0657}$
$Manufacturer_2$	$PQS_1^{2.7583}$	N/A	$PQS_1^{1.0657}$
$Manufacturer_3$	$PQS_1^{2.7583}$	$PQS_1^{1.8133}$	N/A

Table 4.14: Potential PQS selections of the threatening player under Threat Ignorance and Maximum Achievable Profits

Threatening/Threatened	$Manufacturer_1$	$Manufacturer_2$	$Manufacturer_3$
$Manufacturer_1$	N/A	$PQS_3^{3.2277}$	$PQS_3^{2.4181}$
$Manufacturer_2$	$PQS_3^{4.2076}$	N/A	$PQS_3^{2.4181}$
$Manufacturer_3$	$PQS_3^{4.2076}$	$PQS_3^{3.2277}$	N/A

decline in maximum achievable profit of $manufacturer_1$, demands of $manufacturer_2$ and $manufacturer_2$ from $manufacturer_1$ are same. Hence $manufacturer_1$ accepts the demand of $manufacturer_2$ and $manufacturer_3$ accepts the demand of $manufacturer_2$. Resulting PQS decision is $(PQS_1; PQS_2; PQS_1)$ which is the best possible situation for $manufacturer_2$. Resulting PQS decision makes $manufacturer_1$ and $manufacturer_3$ better off besides $manufacturer_2$. In fact existence of a threat comparison like the one in this case is closely related to existence of at least one decision combination which makes at least one decision maker better off and remaining decision makers unchanged at the worst case. A manufacturer considers accepting or ignoring a threat directed to him if the maximum achievable profit decreases when he ignores the threat. A counter PQS in a threat is the one that minimizes the maximum achievable profit of the threatened manufacturer. But since best response functions are actually the decisions made in order to maximize individual return for a given decision set of other players, a threat can not claim a maximum achievable profit below the profit for NE solution. Consequently a comparable threat scheme that contains potential decrease in maximum achievable profit for at least one player, indicates the existence of at least one solution better than NE solution for at least one player and equal to NE solution for the remaining players at the worst case

Table 4.15: Possible Profit Levels for all PQS Decision Combinations (Second Feasible PQS Set)

PQS Combinations	$Manufacturer_1$	$Manufacturer_2$	$Manufacturer_3$
$(PQS_1; PQS_1; PQS_1)$	3.7227	2.8141	2.1078
$(PQS_1; PQS_1; PQS_2)$	3.1700	2.3867	2.0623
$(PQS_1; PQS_1; PQS_3)$	2.3357	1.9838	1.7325
$(PQS_1; PQS_2; PQS_1)$	3.1700	3.3441	1.9538
$(PQS_1; PQS_2; PQS_2)$	2.4975	2.9165	1.7763
$(PQS_1; PQS_2; PQS_3)$	2.0413	2.1308	1.5031
$(PQS_1; PQS_3; PQS_1)$	2.3357	3.0859	1.4772
$(PQS_1; PQS_3; PQS_2)$	2.0413	2.7950	1.4687
$(PQS_1; PQS_3; PQS_3)$	1.8268	2.4394	1.2494
$(PQS_2; PQS_1; PQS_1)$	3.9748	2.3867	1.9538
$(PQS_2; PQS_1; PQS_2)$	3.4715	2.0778	1.7763
$(PQS_2; PQS_1; PQS_3)$	2.9705	1.7335	1.5031
$(PQS_2; PQS_2; PQS_1)$	3.4715	2.9165	1.5894
$(PQS_2; PQS_2; PQS_2)$	3.1370	2.2558	1.5637
$(PQS_2; PQS_2; PQS_3)$	2.6647	1.9222	1.3239
$(PQS_2; PQS_3; PQS_1)$	2.9705	2.7950	1.3157
$(PQS_2; PQS_3; PQS_2)$	2.6647	2.5449	1.3150
$(PQS_2; PQS_3; PQS_3)$	2.0897	2.2302	1.1423
$(PQS_3; PQS_1; PQS_1)$	3.9394	1.9931	1.4772
$(PQS_3; PQS_1; PQS_2)$	3.5607	1.7335	1.4687
$(PQS_3; PQS_1; PQS_3)$	3.0838	1.4922	1.2494
$(PQS_3; PQS_2; PQS_1)$	3.5607	2.1308	1.3157
$(PQS_3; PQS_2; PQS_2)$	3.2230	1.9222	1.3150
$(PQS_3; PQS_2; PQS_3)$	2.8015	1.6654	1.1423
$(PQS_3; PQS_3; PQS_1)$	3.0838	2.4394	1.1532
$(PQS_3; PQS_3; PQS_2)$	**2.8015**	**2.2302**	**1.1544**
$(PQS_3; PQS_3; PQS_3)$	2.5106	1.6858	1.0000

Table 4.16: Desired PQS s from Competitors and Maximum Achievable Profits

Threatening/Threatened	$Manufacturer_1$	$Manufacturer_2$	$Manufacturer_3$
$Manufacturer_1$	N/A	$PQS_1^{2.8141}$	$PQS_1^{2.1078}$
$Manufacturer_2$	$PQS_1^{3.7227}$	N/A	$PQS_1^{2.1078}$
$Manufacturer_3$	$PQS_1^{3.7227}$	$PQS_1^{2.8141}$	N/A

Table 4.17: Potential PQS selections of the threatening player under Threat Ignorance and Maximum Achievable Profits

Threatening/Threatened	$Manufacturer_1$	$Manufacturer_2$	$Manufacturer_3$
$Manufacturer_1$	N/A	$PQS_3^{2.4394}$	$PQS_3^{1.4772}$
$Manufacturer_2$	$PQS_3^{3.0838}$	N/A	$PQS_3^{1.4772}$
$Manufacturer_3$	$PQS_3^{3.0838}$	$PQS_3^{2.4394}$	N/A

Table 4.18: Potential Decreases in Maximum Achievable Profits for Ignored Threats

Threatening/Threatened	$Manufacturer_1$	$Manufacturer_2$	$Manufacturer_3$
$Manufacturer_1$	N/A	0.3748	0.6306
$Manufacturer_2$	0.6389	N/A	0.6306
$Manufacturer_3$	0.6389	0.3748	N/A

and vice versa. For instance, when the first feasible PQS set is used, there were neither an applicable threat comparison nor a solution that meets the requirements stated above. Actually, when second feasible PQS set is used, there are more than one better solutions $\Big((PQS_1; PQS_1; PQS_1)$,$(PQS_1; PQS_1; PQS_2)$,$(PQS_2; PQS_1; PQS_1)$,$(PQS_2; PQS_2; PQS_1)$, $(PQS_2; PQS_3; PQS_1) \quad i.e\Big)$ which make all manufacturers better off and one of them is the best decision combination for $manufacturer_3$. However the dominance of $manufacturer_2$ makes all remaining manufacturers meet his demands.

Chapter 5

CONCLUSIONS

In this chapter, a summary of what is addressed in the thesis, discussions regarding observations extracted from the numerical analysis as well as future opportunities related to the context of the thesis are presented.

A multi-echelon decentralized supply chain system, consisting of independent and non-identical manufacturers, echelon-based centralized distributors and retailers, was modeled. Raw material suppliers and customers were not considered to be decision makers. A sequential, two phased optimization procedure adopting MILP and RHPC was used in order to incorporate decentralized decision making and stochastic behavior of customer demand. There were non-zero and constant lead times related to production and transportation activities of the corresponding decision makers.

Three IS schemes were designed in order to handle problems emerging because of decentralization and consequent information discrepancy. Additional to the base case, NIS scheme, FDIS and HDIS schemes were organized. FDIS enabled the IS parties receive forecasts of the retailer echelon for the remaining of the optimization horizon whereas HDIS enabled the IS parties receive historic demand data belonging to the previous optimization horizon giving the ability to make their own forecasts. Retailer echelon used Winter's Seasonal Forecasting method and having achieved historic demand data, remaining decision makers used ARMA to produce their own forecasts. Seasonal demand was transformed so that stationarity condition was satisfied and ARMA could be used. Under NIS scheme, manufacturers and distributor echelon used Kalman Filtering. A special behavior of distributor and retailer echelons was modeled and named as *preventive ordering*. Different cases of IS strategies were analyzed in terms of profits, inventory and service levels and bullwhip effect, with and without preventive ordering.

Manufacturer competition was incorporated to the system as a full information, non-cooperative and static game as a special level of decentralization. But implicitly, manufacturers act as Stackelberg leaders of distributors and retailers since they announced their decisions in anticipation of the actions belonging to distributor and retailer echelons. Manufacturers had discrete decision alternatives specifying their profit margin and quality level. Resulting selections of the manufacturers determine the allocation of orders given by the retailer echelon for their product. The allocation was carried out by an explicit market share function. Different feasible decision sets were formed. Additional to the sensitivity of the retailer echelon for sales price and quality level, price and quality elasticity of the customers were also modeled. Resulting pricing problem of the retailer echelon was an unconstrained, concave maximization problem with a unique optimal price. A general form of the market share function was formed enabling usage of variable weights associated to sales price and quality level of the manufacturers. The case of three manufacturers was analyzed graphically. A multiple equilibria case and an eligible method for dealing with multiple equilibria was presented. Finally a bi-form game was designed consisting of two stages. First stage was conducted as a full information and non-cooperative game. In the second stage players directed threats to their competitors by claims of selecting the PQS that minimizes the threatened party's maximum achievable profit. The aim of threatening was to make the threatened player to select the PQS that maximizes the threatening party's maximum achievable profit. Players had the obligation of carrying out their threats unless threatened players accept their demands. Furthermore a player only knows the content of the threats either directed by him or to him. Hence second stage was an asymmetric information and cooperative game. Profits and competition penalties were the major performance measures considered in the analysis of upstream competition.

5.1 Main Observations

In this section, a brief interpretation of the numerical results for vertical information sharing and horizontal upstream competition is presented.

5.1.1 Vertical Information Sharing

A supply chain system was constituted by two independent manufacturers, a distributor echelon containing three nodes and a retail echelon consisting of five nodes. All IS strategies yield better profits for all decision makers compared to NIS scheme. There is no strict dominance between FDIS and HDIS among different IS strategies for different decision makers. IS with both echelons results in best performance in terms of profits of all decision makers since it is the case in which the system is closest to centralized operation. Information seems to be more valuable to $manufacturer_2$ since increases in his profit and service level are greater than those of $manufacturer_1$ when IS is between the retailer echelon and manufacturers only. The reason behind this is the shorter transportation lead time of $manufacturer_2$ and consequently more accurate forecasts of the distributor echelon. Particularly for manufacturers, any type of IS yields better service levels than NIS does. In the case of IS with distributors only, inventory levels of both manufacturers are minimum due to insufficient production against accurate forecasts and orders of the distributor echelon. When IS is between the retailer echelon and manufacturers, inventory levels are maximum because of the inaccurate forecasts and orders of the distributor echelon against accurate production batches of the manufacturers.

IS with both echelons is the best strategy in terms of service levels of also the distributor and retailer echelons. Any kind of IS strategy different from NIS offers greater service levels than NIS does. However in the cases of IS with single echelon, service levels exhibit different behavior for different products. When IS is between the retailer and distributor echelons, service level for $product_1$ is greater than the service level obtained in the case of IS with manufacturers and the opposite is true for $product_2$. Due to long transportation lead time of $manufacturer_1$, distributors' forecasts for $product_1$ are less accurate. Therefore after obtaining any kind of demand information from the retailer echelon forecasts, orders and consequently service level of the distributor echelon for $product_1$ increases significantly whereas corresponding improvement in the service level for $product_2$ is not so significant because of the shorter lead time. Hence service level for $product_2$ significantly increases when IS is between the retailer echelon and manufacturers rather than the distributor echelon. Since the service level of the retailer echelon is directly affected by the service level of the distributor echelon, variation in his service level can be interpreted similarly. While the service and profit levels of the retailer echelon are positively correlated for all IS strategies, which is quite intuitive indeed, in the cases of IS with a single echelon, results show the opposite relationship for the profit of distributor echelon obtained from $product_2$. Once again the reason is different transportation lead times of the manufacturers. At the beginning of the optimization horizon, retailer echelon does not place any orders to the distributor nodes with short lead times for $product_2$ instead he uses his initial inventory. When demand information is available to manufacturers only, those distributor nodes assume zero order amounts for the entire optimization horizon and therefore salvage all of their initial inventories. Consequently just after facing positive order amounts from the retailer echelon they have to purchase products from the manufacturers which they could have supplied from initial inventory. The increase in the purchasing cost cannot be compensated by the increase in revenue resulting in less profit.

Bullwhip effect on a decision maker was considered to be the ratio of variance of out going orders to variance of incoming orders. Without preventive ordering, bullwhip effect on retailer echelons are almost equal regardless of product type and IS strategy. Since the variance of customer demand is constant, this meant that order variance of the retailer echelon did not change as well. This result is very intuitive because of customer demand information the retailer echelon possessed. Consequently the changes in bullwhip effect on distributor echelon depend only the changes in variance of orders placed by the distributor echelon. As stated previously, order variance of the distributor echelon for $product_1$ decreases more than the one for $product_2$ does when there was any kind of IS with distributor echelon. But when there is IS with distributor echelon, in the last periods of the optimization horizon, distributor echelon gives zero amount orders knowing that the retailer echelon would not place any orders. The increase in the variance due to those zero order amounts suppresses the insignificant decrease in the order variance of the distributor echelon for $product_2$. When IS is between retailer echelon and manufacturers only, bullwhip effect on the distributor echelon for $product_1$ increases compared to NIS scheme because the inaccurate orders of the distributor echelon are met by informed $manufacturer_1$ resulting in unstable inventory levels and order amounts. Preventive ordering generally tends to increase order variances for both echelons except for the one for $product_2$ of distributor echelon when IS is among both echelons. Main cause is the low service levels resulting in frequent preventive orders. For some cases, bullwhip effect on the distributor echelon is even less when preventive ordering is incorporated. This is because of the substantial increase in the order variance of the retailer echelon. For $product_1$ order variance of the distributor echelon is greater for all cases if preventive ordering is included. However, under IS among both echelons, order variance of the distributor echelon decreased for $product_2$ when preventive ordering is included. Due to the high service level and elimination of the zero order amounts due to the shortages in the last periods of the optimization horizon corresponding order variance exhibits a decline. Bullwhip effect without preventive ordering on the distributor echelon for $product_1$ is greater than the one for $product_2$ except for the case of FDIS among both echelons. When preventive ordering is used, bullwhip effect on the distributor echelon for $prodcut_1$ is again greater than that for $product_2$ except for the cases of FDIS with only distributor echelon and HDIS among both echelons. This is due to the higher service levels for $product_1$ under those cases. For the retailer echelon and under preventive ordering, bullwhip effect for $product_2$ is less for all cases except NIS. This is a result of the satisfaction of highly varying order amounts due to shorter transportation lead of the related manufacturer and consequent unstable inventory levels.

In summary, IS provides better profit and service levels due to either timely coordination of supply and demand or improved accuracy of supply. Longer lead times increase forecast inaccuracies and order variability consequently the bullwhip effect. Any generalizations about the dominance of forecasting with ARMA models or Winter's seasonal forecasting method cannot not be made. Centralization of demand information is the best case in which the impacts of the factors enlisted above are the highest.

5.1.2 Horizontal Upstream Competition

In this part of the analysis, the same setting as the one in the analysis of information sharing was used except the substitutability of the different products. Having access to all kind of information, manufacturers used ARMA models for forecasting customer demand.

For the first feasible PQS set in which price and quality levels are positively correlated, NE and Pareto solutions are equal and there are no competition penalties for neither of the two manufacturers. For the second feasible PQS set with negatively correlated price and quality levels, NE and Pareto optimal solutions are different and $manufacturer_2$ faces a competition penalty. In this case the NE solution is a compromise between increasing sales prices and decreasing market shares. With the incorporation of price and quality elasticity of the customer demand, profit levels of all decision makers for all feasible decision sets decreases except the profit level of the retailer echelon. There are two main causes behind this increase. First one is the pricing power of the retailer and second one is the promotion of quality without any effort of the retailer echelon. The declines in the profit levels of the manufacturers are a result of the decrease in the demand due to the pricing power of the retailer, non-cooperative behaviors of the manufacturers and negative effect of the promotion of the quality level specifically for the second feasible decision set. The distributors suffers from only the decreased demand since their unit profit margins are fixed.

Analysis of the generalized market share shows that increasing the exponential weight of either price or quality level increases competition penalty. If price and quality elasticity of customer demand is incorporated, NE solutions under second feasible PQS set do not change for both manufacturers.

In the case of three manufacturers one unique equilibrium and one multiple equilibria situations are shows graphically. When there are multiple equilibria, one of the solutions strictly dominates the other one hence it was concluded that even if the game was a non-cooperative one the players would select the dominating NE solution. A bi-form game was formed the relationship between the existence of strictly better solutions than initial NE solution and the ability to formulate threats worth analyzing was stated. For the second feasible PQS set, a strictly better solution can be obtained out of a family of solutions which is the best for the dominant player according to the threat analysis.

In summary, NE solutions are basically the compromises between significances of the impacts of price and quality on profit and market shares. Pricing power of the retailer echelon is advantageous for only himself since he independently rationed customer demand. Increased importance given to price and quality by retailer echelon increases competition penalties of the manufacturers caused by tighter competition. Formulation of threats that worth analysis depends on existence of solutions strictly dominant to the initial NE solution. Finally, cooperative behavior provides better performance due to eligibility of making strict agreements dealing with the trust issue faced while simultaneous moves of the manufacturers away from the initial NE solution.

5.2 Future Work

Additional to the existing work in this study, a more number of IS Schemes can be formed consisting of information related to other echelons besides customer demand. Raw material suppliers can also be modeled as decision makers with a cost structure similar to the manufacturers. In addition, intra-echelon centralized structure of the distributor and retailer echelons can be modeled as completely independent nodes with an enhanced optimization approach. A clearance market can be formed with more significant salvage prices affecting the procurement decisions of the supply chain participants. The initial static game between manufacturers can be differently designed to incorporate information asymmetry. Different contract types can also be formed and analyzed under cooperative game theory.

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APPENDIX

Revised Mathematical Model of the Supply Chain System

The sets regarding decision makers, IS schemes, products and time periods are as follows:

Sets:

Set of manufacturers I

Set of distributors J

Set of retailers K

Set of products P

Set of PQS s L

Set of time periods T

Parameters, decision variables of the corresponding decision makers are as follows:

Parameters of Manufacturers:

$fcastman_{p,k,t}$: demand forecast

pu_i: unit purchasing cost

$y_{i,l}$: production yield

$v_{i,l}$: variable production cost

f_i: fixed production cost

lp_i: production lead time

$PCap_i$: production capacity

$rm_{i,l}$: unit revenue

sal_i: unit salvage

$TCap_i$: total transportation capacity

$tr_{i,j}$: unit transportation cost

$g_{i,j}$: transportation lead time

int: annual interest rate

Decision Variables of Manufacturers:

$RP_{i,t}$; raw material purchased

$IR_{i,t}$: raw material inventory

$P_{i,t}$: production amount

$MInr_{i,t}$: finished goods inventory

$at_{i,j,t}$: transportation amount

$Sur_{i,j,t}$: surplus in the transportation amount

$Sla_{i,j,t}$: shortage in the transportation amount

$PS_{i,t}$; production run indicator

Parameters of Distributor Nodes:

$fcastdist_{p,k,t}$: demand forecast

$dt_{j,k}$: unit transportation cost

$sald_{p,j}$: unit salvage

$KD_{p,j}$: inventory capacity

$dl_{j,k}$: transportation lead time

$DTCap_{p,j}$: transportation capacity

$dmargin_{p,j}$: profit margin

Decision Variables of Distributor Nodes:

$atd_{p,j,k,t}$: transportation amount

$dorder_{i,j,t}$: order amount

$DInr_{p,j,t}$: inventory

$Surd_{p,j,k,t}$: surplus in the transportation amount

$Slad_{p,j,k,t}$: shortage in the transportation amount

Parameters of Retailer Nodes:

$KR_{p,k}$: inventory capacity

$fcast_{p,k,t}$: demand forecast

$demand_{p,k,t}$: customer demand

$quota_{j,k}$: quota for order amounts

$rmargin_{p,k}$: profit margin

Decision Variables of Retailer Nodes:

$order_{p,j,k,t}$: order amount

$RInr_{p,k,t}$: inventory

$s_{p,k,t}$: sales amount

$Surr_{p,k,t}$: surplus in the sales amount

$Slar_{p,k,t}$: shortage in the sales amount

Objective function and constraints for Manufacturers:

$revenue = \sum_j \sum_t rm_{i,l} \left(at_{i,j,t} - Sur_{i,j,t} \right)$

$salvage = \sum_j \sum_t sal_i Sur_{i,j,t}$

$raw\ material\ purchasing\ cost = \sum_t pu_i RP_{i,t}$

$raw\ material\ holding\ holding\ cost = \frac{int}{T} \sum_t pu_i IR_{i,t}$

$production\ cost = \sum_t \left(v_{i,l} P_{i,t} + f_i PS_{i,t} \right)$

$finished\ goods\ inventory\ holding\ cost = \frac{int}{T} \sum_t (v_{i,l} + pu_i) IFG_{i,t}$

$transportation\ cost = \sum_j \sum_t tr_{i,j} at_{i,j,t}$

$profitmanufacturer_i = \sum_j \sum_t rm_{i,l} \left(at_{i,j,t} - Sur_{i,j,t} \right) + \sum_j \sum_t sal_i Sur_{i,j,t} - \sum_t pu_i RP_{i,t} - \frac{int}{T} \sum_t pu_i IR_{i,t} - \sum_t \left(v_{i,l} P_{i,t} + f_i PS_{i,t} \right) - \frac{int}{T} \sum_t (v_{i,l} + pu_i) IFG_{i,t} - \sum_j \sum_t tr_{i,j} at_{i,j,t}$

The optimization problem of manufacturers is given as:

$max\ profitmanufacturer_{i,l}$

$s.t.$

$$P_{i,t} \leq PS_{i,t} PCap_i \qquad \forall i, t \ ,$$

$$\sum_{t'=t-lp_i+1}^{t'=t+lp_i-1} PS_{i,t} \leq 1 \qquad \forall i, t \ ,$$

$$\sum_{j} at_{i,j,t} \leq TCap_i \qquad \forall i,t \ ,$$

$$Sur_{i,j,t} - Sla_{i,j,t} = at_{i,j,t} - dorder'_{i,j,t} \qquad \forall i,j,t \ ,$$

$$IR_{i,t} = IR_{i,t-1} + RP_{i,t} - P_{i,t} \qquad \forall i, \forall t = 1..T \ ,$$

$$MInr_{i,t} = MInr_{i,t-1} + y_i P_{i,t-lp_{il}} - \sum_{j} at_{i,j,t} \qquad \forall i,l, \forall t = 1..T \ ,$$

$$RP_{i,0}, IR_{i,0}, PS_{i,0}, at_{i,j,0} = 0 \qquad \forall i \ ,$$

$$MInr_{i,0} = MInr'_i \qquad \forall i \ ,$$

$$RP_{i,t}, IR_{it}, P_{i,t}, MInr_{i,t}, at_{i,j,t}, Sur_{i,j,t}, Sla_{i,j,t} \geq 0 \qquad \forall i,j,t,$$

$$PS_{i,t} \in \{0,1\} \qquad \forall i,t \ .$$

Objective function and constraints for Distributor Nodes:

$revenue = \sum_{i=p}\sum_{j}\sum_{k}\sum_{t}(1+dmargin_{p,j})rm_{i,l}(atd_{p,j,k,t} - Surd_{p,j,k,t})$
$salvage = \sum_{j}\sum_{k}\sum_{t} sald_{p,j}Surd_{p,j,k,t}$
$planned\ purchasing\ cost = \sum_{i=p}\sum_{j}\sum_{t} rm_{i,l}order_{i,j,t}$
$actual\ purchasing\ cost = \sum_{i=p}\sum_{j}\sum_{t} rm_{i,l}(at'_{i,j,t} - Sur'_{i,j,t})$
$holding\ cost = \frac{int}{T}\sum_{i=p}\sum_{j}\sum_{t} rm_{i,l}DInr_{p,j,t}$
$transportation\ cost = \sum_{j}\sum_{k}\sum_{t} dt_{j,k}atd_{p,j,k,t}$
$profitdistributor_p = \sum_{i=p}\sum_{j}\sum_{k}\sum_{t}(1+dmargin_j)rm_{i,l}(atd_{p,j,k,t} - Surd_{p,j,k,t}) +$
$\sum_{j}\sum_{k}\sum_{t} sald_{p,j}Surd_{p,j,k,t} - \Big[\sum_{i=p}\sum_{j}\sum_{t} rm_{i,l}order_{i,j,t} \ \Lambda \ \sum_{i=p}\sum_{j}\sum_{t} rm_{i,l}(at'_{i,j,t} - Sur'_{i,j,t})\Big] -$
$\frac{int}{T}\sum_{i=p}\sum_{j}\sum_{t} rm_{i,l}DInr_{p,j,t} - \sum_{j}\sum_{k}\sum_{t} dt_{j,k}atd_{p,j,k,t}$

The optimization problem of distributor echelon is given as:

$max\ profitdistributor_{p,l}$

$s.t.$

$$DInr_{p,j,t} \leq KD_{p,j} \qquad \forall j,p,t \ ,$$

$$DInr_{p,j,t} = DInr_{p,j,t-1} + \sum_{i=p} dorder_{i,j,t-g_{i,j}} - \sum_{k} atd_{p,j,k,t} \qquad \forall j,p,\forall t = 1..T \ ,$$

$$DInr_{p,j,t} = DInr_{p,j,t-1} + \sum_{i=p} (at'_{i,j,t-g_{i,j}} - Sur'_{i,j,t-g_{i,j}}) - \sum_{k} atd_{p,j,k,t} \qquad \forall j,p,\forall t = 1..T \ ,$$

$$Surd_{p,j,k,t} - Slad_{p,j,k,t} = atd_{p,j,k,t} - order'_{p,j,k,t} \qquad \forall j,k,p,t \ ,$$

$$\sum_{k} atd_{p,j,k,t} \leq DTCap_{p,j} \qquad \forall j,p,t \ ,$$

$$atd_{p,j,k,0} = 0 \qquad \forall j,k,p \ ,$$

$$DInr_{p,j,0} = DInr'_{p,j} \qquad \forall j,k,p \ ,$$

$$atd_{p,j,k,t}, dorder_{i,j,t}, DInr_{p,j,t}, Surd_{p,j,k,t}, Slad_{p,j,k,t} \geq 0 \qquad \forall i,j,k,p,t \ .$$

Objective function and constraints for Retailer Nodes:

$revenue = \sum_{i=p} \sum_{j} \sum_{k} \sum_{t} (1 + dmargin_{p,j} + rmargin_{p,k}) rm_{i,l} (s_{p,k,t} - Surr_{p,k,t})$

$planned\ purchasing\ cost = \sum_{i=p} \sum_{j} \sum_{k} \sum_{t} (1 + dmargin_{p,j}) rm_{i,l} order_{p,j,k,t}$

$actual\ purchasing\ cost = \sum_{i=p} \sum_{j} \sum_{k} \sum_{t} (1 + dmargin_{p,j}) rm_{i,l} (atd'_{p,j,k,t} - Surd'_{p,j,k,t})$

$holding\ cost = \frac{int}{T} \sum_{i=p} \sum_{j} \sum_{k} \sum_{t} (1 + dmargin_{p,j}) rm_{i,l} RInr_{p,k}$

$$profitretailer_{p,l} = \sum_{i=p}\sum_{k}\sum_{t}(1 + dmargin_{p,j} + rmargin_{p,k})rm_{i,l}(s_{p,k,t} - Surr_{p,k,t}) - \Big[\sum_{i=p}\sum_{j}\sum_{k}\sum_{t}(1+ dmargin_{p,j})rm_{i,l}order_{p,j,k,t} \; \Lambda \; \sum_{i=p}\sum_{j}\sum_{k}\sum_{t}(1+dmargin_{p,j})rm_{i,l}(atd_{p,j,k,t} - Surd_{p,j,k,t})\Big] - \frac{int}{T}\sum_{i=p}\sum_{j}\sum_{k}\sum_{t}(1 + dmargin_{p,j})rm_{i,l}RInr_{p,k}$$

The optimization problem of retailer echelon is given as:

$max \; profitretailer_{p,l}$

$s.t.$

$$RInr_{p,k,t} \le KR_{p,k} \qquad \forall k,p,t \; ,$$

$$RInr_{p,k,t} = RInr_{p,k,t-1} + \sum_{j} order_{p,j,k,t-dl_{j,k}} - s_{p,k,t} + Surr_{p,k,t} \qquad \forall k,p,\forall t = 1..T \; ,$$

$$RInr_{p,k,t} = RInr_{p,k,t-1} + \sum_{j}(atd'_{p,j,k,t-dl_{j,k}} - Surd'_{p,j,k,t-dl_{j,k}}) - s_{p,k,t} + Surr_{p,k,t} \qquad \forall k,p,\forall t = 1..T \; ,$$

$$s_{p,k,t} - fcast_{p,k,t} = Surr_{p,k,t} - Slar_{p,k,t} \qquad \forall k,p,t \; ,$$

$$order_{p,j,k,t-dl_{j,k}} \le \sum_{j'} order_{p,j',k,t-dl_{j',k}} quota_{j,k} \qquad \forall j,k,p,t \; ,$$

$$s_{p,k,0} = 0 \qquad \forall k,p \; ,$$

$$RInr_{p,k,0} = RInr'_{p,k} \qquad \forall k,p \; ,$$

$$s_{p,k,t}, order_{p,j,k,t}, RInr_{p,k,t}, Surr_{p,k,t}, Slar_{p,k,t} \ge 0 \qquad \forall j,k,p,t \; .$$

Parameter Values of the Manufacturers (Information Sharing)

Table 5.1: Parameter Values of the Manufacturers

Parameter	**Value**
pu_i	30
y_i	0.95
v_i	50
f_i	2000
lp_i	2
$PCap_i$	40000
rm_i	250
sal_i	20
int	20%

Parameter Values of the Distributor Echelon (Information Sharing)

Table 5.2: $dt_{j,k}$

	$Retailer_1$	$Retailer_2$	$Retailer_3$	$Retailer_4$	$Retailer_5$
$Distributor_1$	20	22	24	26	28
$Distributor_2$	19	19	19	19	19
$Distributor_3$	18	16	14	12	10

Table 5.3: $sald_{p,j}$

	$Distributor_1$	$Distributor_2$	$Distributor_3$
$Product_1$	10	10	10
$Product_2$	10	10	10

Table 5.4: $KD_{p,j}$

	$Distributor_1$	$Distributor_2$	$Distributor_3$
$Product_1$	10000	9000	8000
$Product_2$	10000	9000	8000

Table 5.5: $dl_{j,k}$

	$Retailer_1$	$Retailer_2$	$Retailer_3$	$Retailer_4$	$Retailer_5$
$Distributor_1$	1	1	1	1	1
$Distributor_2$	2	2	2	2	2
$Distributor_3$	3	3	3	3	3

Table 5.6: $DTCap_{p,j}$

	$Distributor_1$	$Distributor_2$	$Distributor_3$
$Product_1$	12000	11000	10000
$Product_2$	12000	11000	10000

Table 5.7: $dmargin_{p,j}$

	$Distributor_1$	$Distributor_2$	$Distributor_3$
$Product_1$	62.5	75	87.5
$Product_2$	62.5	75	87.5

Parameter Values of the Retailer Echelon (Information Sharing)

Table 5.8: $KR_{p,k}$

	$Retailer_1$	$Retailer_2$	$Retailer_3$	$Retailer_4$	$Retailer_5$
$Product_1$	3500	3100	2600	2200	1800
$Product_2$	3200	2800	2300	1900	1500

Table 5.9: Process Parameters of Customer Demand

Parameter	$Retailer_1$	$Retailer_2$	$Retailer_3$	$Retailer_4$	$Retailer_5$
level	3000	2600	2100	1700	1300
increment	100	100	100	100	100
σ	200	200	200	200	200

Table 5.10: $quota_{j,k}$

	$Retailer_1$	$Retailer_2$	$Retailer_3$	$Retailer_4$	$Retailer_5$
$Distributor_1$	0.1	0.2	0.3	0.4	0.5
$Distributor_2$	0.4	0.4	0.4	0.4	0.4
$Distributor_3$	0.5	0.4	0.3	0.2	0.1

Table 5.11: $rmargin_{p,k}$

	$Retailer_1$	$Retailer_2$	$Retailer_3$	$Retailer_4$	$Retailer_5$
$Product_1$	118.125	114.75	111.375	108	104.625
$Product_2$	118.125	114.75	111.375	108	104.625

Table 5.12: Parameters for the Pricing Problem of Retailer Nodes

Parameter	$Retailer_1$	$Retailer_2$	$Retailer_3$	$Retailer_4$	$Retailer_5$
$pelasticity_k$	1	1.2	1.4	1.6	1.8
$qelasticity_k$	1.8	1.6	1.4	1.2	1
$baseprice_k$	375	375	375	375	375

GAMS Statistics

Table 5.13: Number of Variables and Constraints regarding the MILP Models ($t = 0$)

	Manufacturers	**Distributor Echelon**	**Retailer Echelon**
Number of Variables	5120	17902	13534
Number of Constraints	994	2682	3168

Table 5.14: Solution Times (Cumulative starting from $t = 0$)

Problem	**Time (Seconds)**
Information Sharing	2734
Manufacturer Competition (Two Manufacturers)	1723
Manufacturer Competition (Two Manufacturers with variable weight of sales price)	84055
Manufacturer Competition (Two Manufacturers with variable weight of quality level)	33609
Manufacturer Competition (Two Manufacturers with Price and Quality Elasticity)	1946
Manufacturer Competition (Three Manufacturers)	8834

VITA

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