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STACKELBERG LEADERSHIP AND EFFECTIVENESS OF DEMAND DISRUPTION MANAGEMENT IN A THREE-TIER ELECTRONICS SUPPLY CHAIN

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STACKELBERG LEADERSHIP AND
EFFECTIVENESS OF DEMAND DISRUPTION MANAGEMENT
IN A THREE-TIER ELECTRONICS SUPPLY CHAIN

A DISSERTATION APPROVED FOR THE
SCHOOL OF INDUSTRIAL ENGINEERING

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Abstract

Management of electronics supply chains has become increasingly complicated due to both a rising dependence on Contract Electronics Manufacturers (CEMs) and the increased dominance of retailing giants. This paper analyzes the effects of different leadership structures on the relative profit of each member of a three-tier electronics supply chain that consists of a CEM, an Original Equipment Manufacturer (OEM), and a Retailer. Our decentralized supply chain setting is governed by a wholesale price contract, and we assume that each supply chain member faces an increasing marginal unit cost function. We conduct a comparative analysis with a centralized supply chain (i.e., a vertically integrated company with business divisions acting as CEM, OEM, and Retailer). Three different demand functions are considered: linear, exponential, and stochastic. Our results show that supply chains in which the Retailer acts as the Stackelberg leader have the highest optimum profit regardless of the demand function. Results also show that the allocation of unit cost between the CEM, OEM and Retailer affects the profit distribution profile. Finally, we also study the effectiveness of demand disruption management in the decentralized supply chain setting where the OEM is the leader. A penalty cost is incurred by the Retailer when a demand disruption occurs, i.e. when actual demand deviates from the original forecast. We find exact analytical solutions of the effectiveness of managing disruptions when the consumer demand is linear, and we provide numerical examples as an illustration when the consumer demand is either linear or exponential.

1. INTRODUCTION

Fueled by the technology recession in 2000-2001, the global electronics supply chain has been fundamentally altered by the rise of Contract Electronics Manufacturers (CEMs). Until a few years ago, Original Equipment Manufacturers (OEM) such as IBM and Motorola used in-house facilities to manufacture most major sub-assemblies for their end products. They provided sub-assemblies to internal business units and also sold them in the marketplace. For example, hard disk drives manufactured by IBM's Storage System Division were sold to OEMs, consumers, distributors, and were used in other IBM products such as personal computers and servers. In such a vertically integrated supply chain, IBM had complete visibility of all of its component suppliers and exercised near total control of operations. Of course, operating electronics supply chains has never been easy, and even in a vertically integrated supply chain, the issue of centralized versus decentralized supply chain decision making can be contentious.

Recently the IBM Institute of Business Value (2008) reported that CEOs in the electronics industry are striving for global integration to a much greater extent than their peers in other industries. Global integration aims to build the supply chain by virtually linking individual providers (nodes) who are the best at executing their particular task, which can be a very challenging endeavor. Unlike the days of vertical integration, these nodes do not have to be owned by one firm and can be situated anywhere in the world.

Consider Apple's first generation iPod Nano. Apple (OEM) outsourced production of the Nano to Foxconn Technology Group (CEM) who assembled over one hundred components. One of the key components on this first generation was the PortalPlayer microchip, which was built by the Taiwan Semiconductor Manufacturing Corp. (TSMC) and United Microelectronics Corp. (UMC). After a very long, complex manufacturing process involving hundreds of steps and extraordinarily expensive machinery, the chips were coated in plastic and made ready for assembly by Silicon-Ware in Taiwan and Amkor in Korea. The finished microchip was then warehoused in Hong Kong before being transported to China where the Nanos were assembled by Foxconn.

Carbone (2004) wrote that market researcher iSuppli predicted that the global contract electronics manufacturing (CEM) industry will experience a compound annual growth rate (CAGR) of 11.1 per cent from about $159 billion in 2003 to $307 billion in 2008. However, iSuppli also reported in an article "CEM Industry to Transform by 2013" published by EMT WorldWide (2008) that the CEM industry is undergoing a period of deceleration and consolidation. Revenue is expected to rise at a CAGR of 7.2% from $305.5 billion in 2007 to $432.3 billion in 2012. The latest development in this consolidation trend was the $3.6 billion acquisition of Solectron by Flextronics in October 2007. Flextronics now has the broadest worldwide electronics manufacturing services capabilities in the electronics outsourcing industry. For OEM buyers involved in outsourcing decision, this means less competition for manufacturing business.

iSuppli further reported that the CEMs are reexamining their relationships with their OEM consumers. Conflicts between OEMs and CEMs over decisions regarding which component suppliers to work with and which parts to buy have become common nowadays. There is a wide range of potential engagement models between OEM and their CEMs that vary between fully outsourced models and total-control models. In a fully outsourced model, the CEM is responsible for most supply chain activities. On the other hand, in a total control model, the OEM retains control of most supply chain activities except for the actual manufacturing. Often, hybrid models that are a mix of the fully outsourced and total-control strategies have been developed to suit the unique manufacturing and service needs of the OEM.

While the OEMs are still searching for the “winning model” in their relationship with the CEMs, there has been a dramatic increase in the relative powers of retailers and manufacturers of consumer products. Wang & Liu (2007) reported that the retailers in China consumer electronics hold a dominant position such that they are able to affect their supplier's production and delivery decisions. To gain greater market shares, the retailers squeeze the manufacturers by setting an even lower wholesale price – that means manufacturers need to sacrifice some profit in exchange of market share.

Given these complexities, OEMs often find themselves confused and ask 'who controls the supply chain?' and 'what the right engagement model is?' Ericsson (OEM), for example, sources the entire manufacturing of the cell phones from Flextronics (CEM), and sells through Retailers like Best Buy, Radio Shack, Office Depot, and Wal-Mart.

In this dissertation, we investigate the impact of leadership on a single-period, three-tier decentralized electronics supply chain that consists of a Contract Electronics Manufacturer (CEM), an Original Equipment Manufacturer (OEM), and a Retailer (Figure 1). We consider the two most commonly used functional relationship in demand studies, i.e. the linear and the exponential demand functions. We apply game-theory concepts to try to explain the results of interactions between the CEM, the OEM and the Retailer. Specifically, we apply the Stackelberg solution concept, whose central theme lies in the assumption that the leader, occupying the higher level of hierarchy, can choose his strategy to optimize his operation by taking into account the rational reactions of followers. We formulate a model with a serial supply chain governed by a simple wholesale price contract. We consider the contract sequence as a proxy for the relative power of the supply chain member.

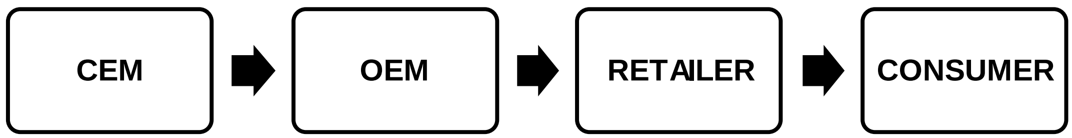

Figure 1 Three-tier electronics supply chain.

To reflect the volatility of the electronics industry, we also consider a stochastic demand function in a two-period newsvendor supply chain setting. We apply two-period stochastic programming with recourse model. In the first period, a production plan is created based on a forecast of market demand that decreases linearly with price and is used for purposes such as procurement of raw materials and capacity planning. In the second period, the product is sold in the retail market and the actual market demand is known. The difference between the actual consumer demand faced by the Retailer and the initial forecast given to the OEM and CEM is defined as demand disruption.

Finally, we study the impact of the demand disruption management in a two-period, three-tier decentralized electronics supply chain that consists of a CEM, a powerful OEM, and a Retailer. The concept of disruption management was introduced by Yu (1998) in the context of airline equipment and crew rescheduling problems that occur when unexpected events create schedule disruptions. Disruption management is concerned with minimizing the impact of the disruption once the disruptive event has occurred. When actual consumer demand is higher than the forecast (positive disruption), overtime production and expedited delivery are required. On the other hand, when actual demand is lower than the forecast (negative disruption), costs for holding excess inventory and perhaps disposal are incurred. A cost-effective response to a demand disruption generally must consider the cost of deviating from existing production plans. The earliest publication on disruption management in a supply chain context is by Qi et al. (2004).

The demand disruption can be generalized as a multi-tier two-period extension of the classical newsvendor problem. In contrast to the single-period newsvendor problem, decision makers in the multi-tier two-period problem use the demand information obtained in the first period to refine their decisions during the second period. Donohue (2000), for example, writes that this updated demand information for fashion goods can be gathered from trade shows, marketing research, etc. She does not use the term “demand disruption” in her two-period manufacturer-distributor newsvendor model. In contrast, Xia et al. (2004) define “demand disruption” as temporary demand rate changes which are often caused by promotional sales. An extensive literature review on various extensions of the classical newsvendor problem can be found in Khouja (1999) and Petruzzi and Dada (1999).

This study contributes to the literature in the following ways. We investigate the effect of different leadership in a three-tier supply chain with a CEM, an OEM, and a Retailer, while most papers to date consider a two-tier supply chain with a manufacturer and a retailer. Our three-tier model corresponds to what we see in practical world. The supply chains of the global electronics industry have steadily disaggregated - OEMs that formerly manufactured most products in-house (such as IBM and Hewlett Packard) have outsourced production to CEMs, while at the same time major consumer electronics retailers (such as Best Buy) reportedly uses its power to buy products at the lowest cost possible and pass the gains on to the consumer through extremely low prices. We consider increasing marginal unit cost in our model to reflect the volatility nature of the electronics supply chain while others consider fixed unit cost. We show the impact of the demand randomness (as additive disruption in the linear demand function) to the optimum supply chain profit. We show the impact of unit cost distribution among the supply chain members on the overall supply chain profit under different leadership. We also investigate the demand disruption management in a three-tier supply chain with a CEM, a powerful OEM, and a Retailer, while most papers to date consider a two-tier supply chain with one manufacturer and one or many retailer(s). We find the exact analytical solutions of the effectiveness of managing the disruption when the consumer demand function is linear, and we provide numerical examples as an illustration when the consumer demand function is either linear or exponential. We show that the production plan for the exponential demand case is more robust relative to the linear demand case.

The rest of this paper is organized as follows. Section 2 examines relevant literature on supply chain contracts, leadership structure, and demand disruption. Section 3 defines our supply chain model for both the centralized and decentralized cases. Section 4 examines the impact of different leadership when consumer demand decreases linearly in price, section 5 examines impact when demand decreases exponentially in price, and section 6 examines impact when demand is stochastic. In section 7 we examine the methods to manage the supply chain when there is a disruption to the original demand function (linear and exponential). We include in section 4, 5, 6 and 7 the use of numerical approach to study the supply chain optimal decisions and profits, and we explore how the retail price, wholesale prices, and profits are affected by changes in the leadership structure (section 4, 5, an 6) and by changes in the demand (section 7). Concluding remarks are provided in section 8.

2. LITERATURE REVIEW

In many instances in the supply chain literature, Stackelberg games have been applied to inventory and production issues, wholesale and retail pricing strategies, and outsourcing. The players in these non-cooperative supply chain settings are primarily concerned with optimizing their own objectives. When these objectives are uncoordinated, the supply chain as a whole encounters a significant loss of efficiency. Optimal performance can be achieved only if each supply chain member's objective becomes aligned with the supply chain's objective. A number of authors have studied mechanisms to achieve supply chain coordination under different Stackelberg leadership. Most of these papers, however, focus on the upstream firm (for example, the manufacturer or the supplier) dominance over the typically smaller downstream firm (the retailer).

Lariviere & Porteus (2001) propose a simple contract with a wholesale price as the only contract parameter. They examine a single-period model in which a manufacturer sells a single product to a retailer facing uncertain demand. The manufacturer acts as a Stackelberg leader by offering a wholesale price proposition. If the retailer accepts the contract offer, he must decide how much to order from the manufacturer and at what price he will sell in order to maximize his profit.

Jeuland and Shugan (1983) show that the decisions of each member in a distribution channel do affect the other channel members' profits and actions. In the simple manufacturer-retailer channel, uncoordinated and independent channel members' decisions over profit margins results in higher price to the end consumer, which leads to lower profits for both the manufacturer and the retailer. They show that the supplier can use a quantity discount schedule to induce the retailer to choose the channel-optimal retailing price.

Ertek & Griffin (2002) develop and analyze two cases wherein each the supplier and the buyer has dominant bargaining power. Due to the increased computing power and internet access, consumers now have access to much more information including price, quality and service features of several competing products, thus increases their bargaining position when acquiring goods and services. On the other hand, if the number of suppliers is limited or reduced through consolidation, then a supplier's bargaining position is increased. In their model, the buyer operates under a simple deterministic EOQ model and sets the retail price while the supplier sets the wholesale price and determines production quantities. They show that the optimal solution in the buyer-driven case is achieved when the buyer uses only a multiplier (of the wholesale price) to determine the markup.

Viswanathan and Wang (2003) study the effectiveness of namely volume discount and quantity discount contracts as coordination mechanisms in distribution channel with the vendor acting as the Stackelberg leader and the retailer acting as the follower.

Choi (1991) investigates a channel structure with two competing manufacturers and one retailer that sells both manufacturers' products. Three non-cooperative games of different leadership structures between the two manufacturers and the retailer are considered, i.e. Manufacturer Stackelberg, Nash Equilibrium, and Retailer Stackelberg.

Zhao and Wang (2002) investigate a distribution channel consisting of a manufacturer who outsources her production distribution/retailing function to an independent downstream distributor/retailer. Both manufacturer and distributor face increasing production/ordering costs and incur a linear inventory holding cost. The demand at the distributor is deterministic and price-sensitive. They show that there exists a manufacturer's wholesale price schedule that induces both parties to adopt channel-optimal policies. The manufacturer has complete information about distributor's cost parameters and demand function that represents its dominant power over the distributor.

Gerchak and Wang (2004) extend the previous model to include multiple suppliers who each provide different (complementary) components in an assembly setting. They show that the supply chain performs better under a revenue sharing contract than under a wholesale price contract. In this setting the supplier who delivers the fewest components determines the quantity of the finished product that can be assembled, leaving a surplus of components from the other suppliers. In anticipation of this, each supplier will act strategically to minimize the impact on its profits caused by such a surplus of components.

Such opportunistic behavior by each member of the supply chain can lead to disastrous financial results especially in the electronics industry. Hewlett Packard, for example, received inflated forecasts from retailers, which led to excess production capacity and excess inventory of their LaserJet printers in the 1990s. Cachon and Lariviere (2001) propose two types of compliance regimes: (1) forced compliance, where the supplier is forced to install a given capacity in advance (once he accepts a contract from the manufacturer) and (2) voluntary compliance, where the supplier can set the capacity at a level which will maximize their expected profit. In their model, they consider a manufacturer who sells a single product with uncertain demand. The manufacturer contracts with a single supplier, who must install a certain capacity level before the actual demand is observed. A final order will be submitted by the manufacturer once the demand is realized. They show that the compliance regime plays an important role in the supply chain performance.

Donohue (2000) studies a one-manufacturer one-distributor supply chain model for high-fashion, seasonal products. Similar to Cachon and Lariviere's work, two periods are considered. In the first period, the distributor places an order to the manufacturer based on uncertain demand predictions and a large range of possible demand scenarios. In the second period, more current market information is available and the distributor updates its forecast. The manufacturer produces items over the two periods, but the orders are filled in one shipment before the selling season begins. Donohue shows that there exists a two-tier wholesale pricing scheme with buyback contract that coordinates the supply chain and maximizes the total profit. Forced compliance is assumed in this study.

In our study, we use a very similar three-tier supply chain model used by Munson & Rosenblatt (2001) and Ding & Chen (2008). Munson & Rosenblatt

(2001) consider constant demand and the objective is to minimize cost. Ding & Chen (2008) consider positive stochastic demand and the objective is to maximize profit. Our work considers price-sensitive demand and the objective is to maximize profit. Our decentralized supply chain model is governed by a wholesale price contract with forced compliance while they use a quantity discount contract as the coordination mechanism. Cachon (2003) notes that although a wholesale price contract is generally not considered a coordinating contract, it is worth studying because it is commonly used in practice in part due to its simplicity. For example, a supplier may prefer a wholesale price contract over a different coordinating contract if the additional administrative burden associated with the coordinating contract exceeds the supplier's potential profit increase.

Our study in the demand disruption is closely related to the work of Qi et al. (2004). They examine the impact of demand disruption in a two-period one-supplier one-retailer supply chain model. In the first period, a production plan is developed before the demand is known. In the second period, the product is sold in the retail market after making adjustment to the original production plan. They show that under certain wholesale quantity discount policies (with the supplier as Stackelberg leader), the demand disruption can be managed leaving both the supplier and the retailer better off. Xu et al. (2006) study a similar supply chain coordination model but under production cost disruptions.

These two studies consider a two-tier supply chain, while our work considers three-tier supply chain with increasing unit cost. Table 1 summarizes the relevant literature as well as the contribution of this study.

Table 1 Summary of the relevant literature.

Author(s)	Supply Chain Model						
	n-Tier	m-Period	Stackelberg Leader	Demand Function	Cost Function	Coordination Mechanism	Disruption
Jeuland and Shugan (1983)	2	1	Nash Equilibrium	Price-sensitive downward sloping	Fixed unit cost	Quantity discount & profit sharing	No
Ertek and Griffin (2002)	2	1	Buyer, Supplier	Linear	Fixed unit cost at supplier & variable unit cost at buyer	Wholesale price	No
Munson and Rosenblatt (2001)	3	1	Manufacturer (middle)	Constant	Fixed setup cost & fixed unit holding cost	Quantity discount	No
Ding and Chen (2008)	3	1	Manufacturer (middle)	Stochastic	Fixed ordering cost and fixed unit production cost	Wholesale price & Flexible Return Policies	No
Zhao and Wang (2002)	2	>1	Manufacturer	Linear	Increasing marginal prod. cost & fixed unit holding cost	Wholesale price & lump sum payment	No
Visnawathan and Wang (2003)	2	1	Vendor	Price-sensitive downward sloping	Fixed ordering cost and fixed unit production cost	Volume discount & quantity discount	No
Choi (1991)	2	1	Manufacturer, Retailer, Nash Equilibrium	Price-sensitive downward sloping	Fixed unit production cost	Wholesale price	No
Qi et al. (2004)	2	2	Supplier	Linear	Fixed unit production cost	Quantity discount	Demand
Donohue (2000)	2	2	Manufacturer	Stochastic	Fixed unit cost	Wholesale price with buyback	Demand
Cachon and Lariviere (2001)	2	2	Manufacturer	Stochastic	Fixed unit production cost	Wholesale price	Demand
Lariviere and Porteus (2001)	2	1	Manufacturer	Stochastic	Fixed unit production cost	Wholesale price	No
Xu et al (2006)	2	2	Supplier	Linear, exponential	Fixed unit production cost	Quantity discount	Prod. Cost
Gerchak and Wang (2004)	2	1	Assembler	Stochastic	Fixed unit production cost	Wholesale price & revenue sharing	No
This paper	3	2	CEM, OEM, Retailer	Linear, exponential, stochastic	Increasing marginal unit cost	Wholesale price	Demand

3. THE BASIC MODEL OF A SUPPLY CHAIN

In our three-tier electronics supply chain, the CEM manufactures a single product and sells to the OEM who adds further value to the product and sells to the Retailer, who sells to the consumer market after incurring some marketing expenses as well as operating costs (rent, utilities, labor, etc.) The product lead time is deterministic, and without loss of generality is assumed to be zero.

Due to the volatile nature of the electronics supply chain, we assume that each supply chain member faces an increasing marginal unit cost function. As the consumer demand increases, the demand for components and the resources to produce also increases. These components and resources (such as the assembly line) are specific to electronics industry, meaning additional investment is needed to increase output (capacity). However, the component manufacturers have always been reluctant to make a large investment in capacity expansion because the machinery and the equipment may be technologically obsolete within a few years. The demand and supply imbalance eventually leads electronics industry to a seller's market. Banker et al. (1998) and Eliashberg & Steinberg (1993) provide a good discussion on the usage of the increasing marginal cost function.

A decreasing marginal unit cost function applies to many retail industries. Consumers can obtain quantity discounts by purchasing materials and supplies in bulk through warehouse clubs such as Sam's Club and Costco. A linear cost function (constant marginal cost function) applies to the software industry. The fixed costs of developing an operating system, for example, can be very high, but the costs of producing one extra copy are practically zero.

We assume no finished goods inventory exists at any member of the supply chain at the beginning of the first period. Production lead-times at CEM and ordering/processing lead-times at OEM/Retailer are zero. Consumer market demand is satisfied in its entirety and no quantity is leftover in the supply chain at the end of the second period.

3.1 Model of a Supply Chain with Deterministic Demand Function

We first study the impact of leadership in the two-period supply chain where the consumer demand is deterministic and price dependent. As a benchmark, we first consider a model where the CEM, OEM, and the Retailer are owned by one firm (see Figure 2). The product unit cost is where is the marginal cost coefficient. In the first period, a production plan is created based on a forecast market demand and is used for purposes such as procurement of raw materials and capacity planning. In the second period, the product is sold in the retail market at retail price and the actual market demand is known and matches the initial forecast . We consider the two most commonly used mathematical functions for representing a downward-sloping price versus demand relationship: (1) linear and (2) exponential . In the linear demand function, is the market scale (i.e. the maximum possible demand), is the price-sensitive coefficient, and . In the exponential demand function, is also the market scale, is the demand elasticity, and . While the linear demand function is mathematically convenient, the exponential demand function is a closer estimate of reality.

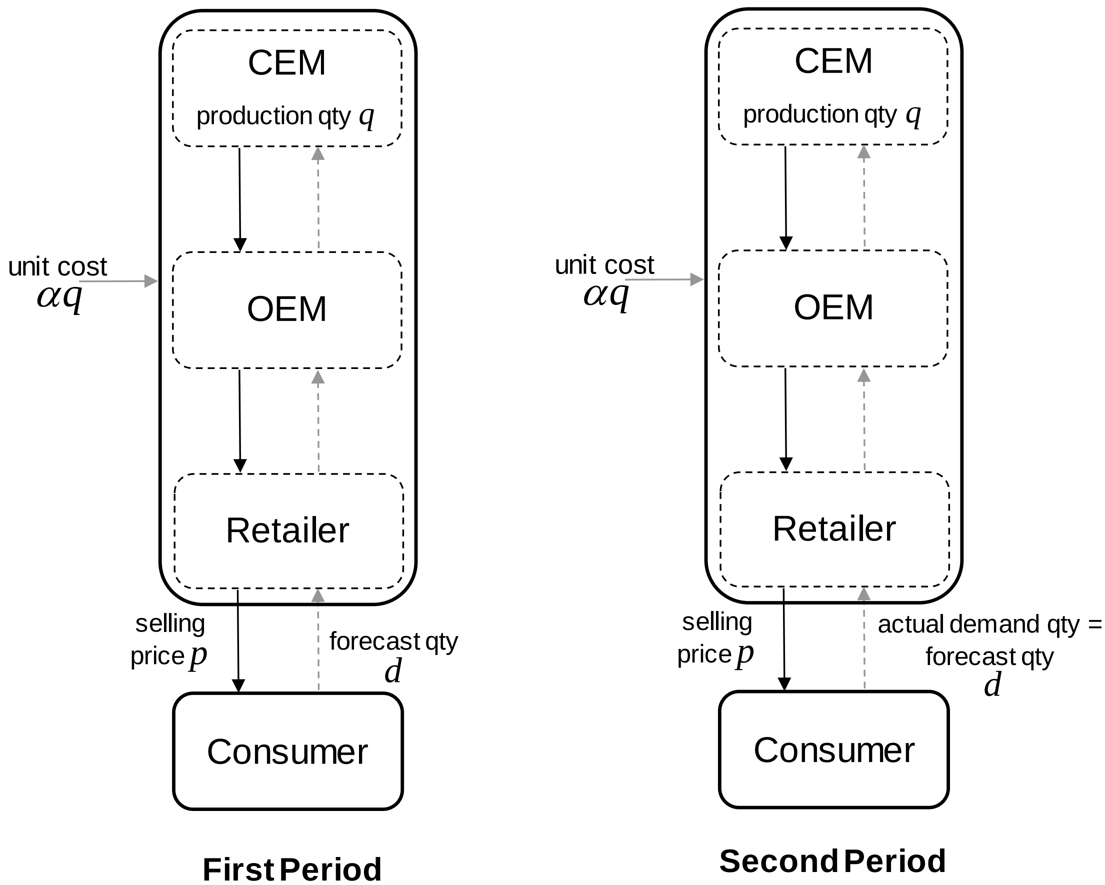

Figure 2 Centralized supply chain model with deterministic demand function.

The centralized supply chain owner maximizes the expected profit by setting the retail price to the value obtained from the following optimization problem:

(1)

Differentiating with respect to retail price , we obtain as necessary and sufficient conditions for profit maximization:

To investigate the impact of different leadership in the decentralized model shown in Figure 3, we construct the effective demand and the cost function that each supply chain member faces as a result of the successive offering of contracts. The supply chain member with more bargaining power, thus the Stackelberg leader, offers a contract in terms of a wholesale price. The supply chain member with less bargaining power (the follower) would have to react to the leader's contract offer by deciding the quantity.

In the first period, the Retailer forecasts to OEM an order quantity based on the forecast market demand . The OEM, in turn, informs the CEM the intent to order quantity . Accordingly, the CEM creates a production plan of quantity . The actual market demand is realized in the second period, and in the deterministic case, it equals to the forecast . The Retailer buys the product from the OEM at a certain unit wholesale price and incurs unit cost (includes advertisement cost, setup and ordering cost, etc.) of , where is the marginal unit cost coefficient at the Retailer.

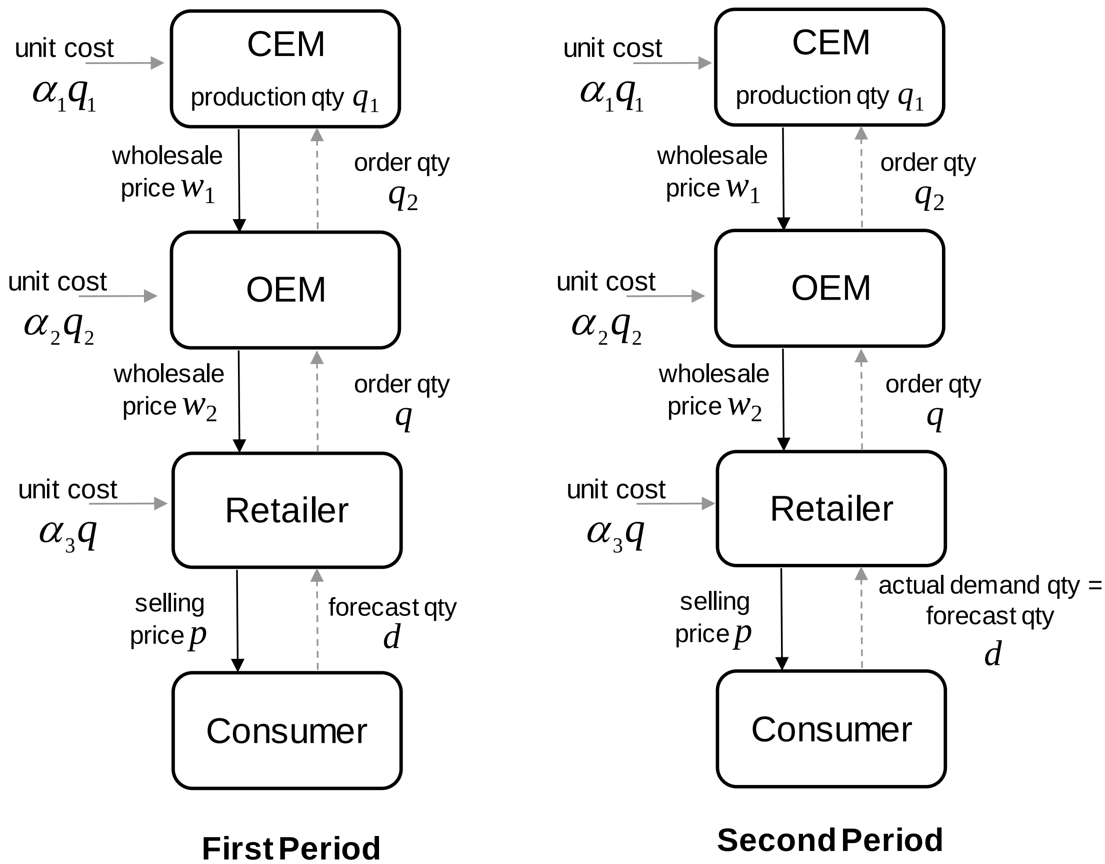

Figure 3 Decentralized supply chain model with deterministic demand function.

The OEM buys the product from the CEM at a certain unit wholesale price and incurs unit cost (includes setup cost and ordering cost, final assembly and test cost) of , where is the marginal unit cost coefficient at the OEM. The CEM manufactures the product at unit cost (includes material cost and labor and load) of , where is the marginal unit cost coefficient at the CEM. Since the contract offered stipulates forced compliance, and assuming there is no leftover quantity in the supply chain at the end of the second period, we have .

The objective function of each supply chain member in the decentralized model is to maximize its own profit. By applying the first and second-order conditions from equations (2) and (3), we obtain the optimal quantity solution of the entire supply chain. We then can calculate the offered wholesale prices and the maximum supply chain profit.

Depending on the situation, the bargaining power possessed by each supply chain member can vary significantly. Three scenarios are considered in our study:

1. The Retailer has more bargaining power than the OEM and the CEM, and thus is the Stackelberg leader. This scenario arises in markets where the Retailers' sizes are large. For example, large retailers like Best Buys and Wal-Mart can decide their margin on sales and offer a "take-it-or-leave-it" contract to the OEM that specifies an amount of money (unit wholesale price) they are willing to spend on the product. The OEM accepts the contract by deciding the quantity . Towards the CEM, the OEM sets the unit wholesale price and the CEM decides the production quantity .

2. The OEM has more bargaining power than the CEM and the Retailer, and thus is the Stackelberg leader. The OEM sets the wholesale price to the CEM as well as to the Retailer. The CEM decides the production quantity , and the Retailer decides the order quantity (hence, the retail price). This scenario arises in markets where the demand of the OEM's product exceeds the supply. For example, the initial demand for Apple's iPod Nano was very high (the first million units sold in only 17 days) and some consumers had to wait weeks before they could get the product. At the same time, the technology to build these products is not complicated, and an OEM with brand recognition (e.g., Apple) can easily move the manufacturing process from one CEM (e.g., Foxconn or Asustek Computer) to another. Thus, Apple has the bargaining power. The consumers respond to the Apple brand and not to the big box retailer or to the unnamed factories making the products. The OEM seeks to maximize its margin on sales while squeezing profit from its suppliers (CEMs) and also from Retailers. Suppliers are mostly concerned with obtaining orders from the OEMs, and the Retailers are mostly concerned with stockouts.

3. The CEM has more bargaining power than the OEM and the Retailer, and thus is the Stackelberg leader. The CEM offers the wholesale price to the OEM, and the OEM decides the order quantity The OEM, in turn, offers the wholesale price to the Retailer who decides the order

quantity (hence, the retail price). An example of this scenario is where the transfer of the production process and technology as well as the supply chains to another CEM or back in-house is very costly. Up to 80% of worldwide tablet PC shipments (such as Apple's iPad, Amazon's Kindle, and Barnes & Nobel's Nook) are manufactured by Foxconn. It will be extremely hard for the OEMs to switch from Foxconn, given the complexity of reworking assembly lines and supply chains.

We assume all supply chain members possess the complete information when making their decisions. In the third scenario, for example, the CEM knows the OEM's response (order quantity) for a given wholesale price offered ( ), hence, the resulting profit. Taking this information into account, the CEM will choose the production quantity to maximize own profit.

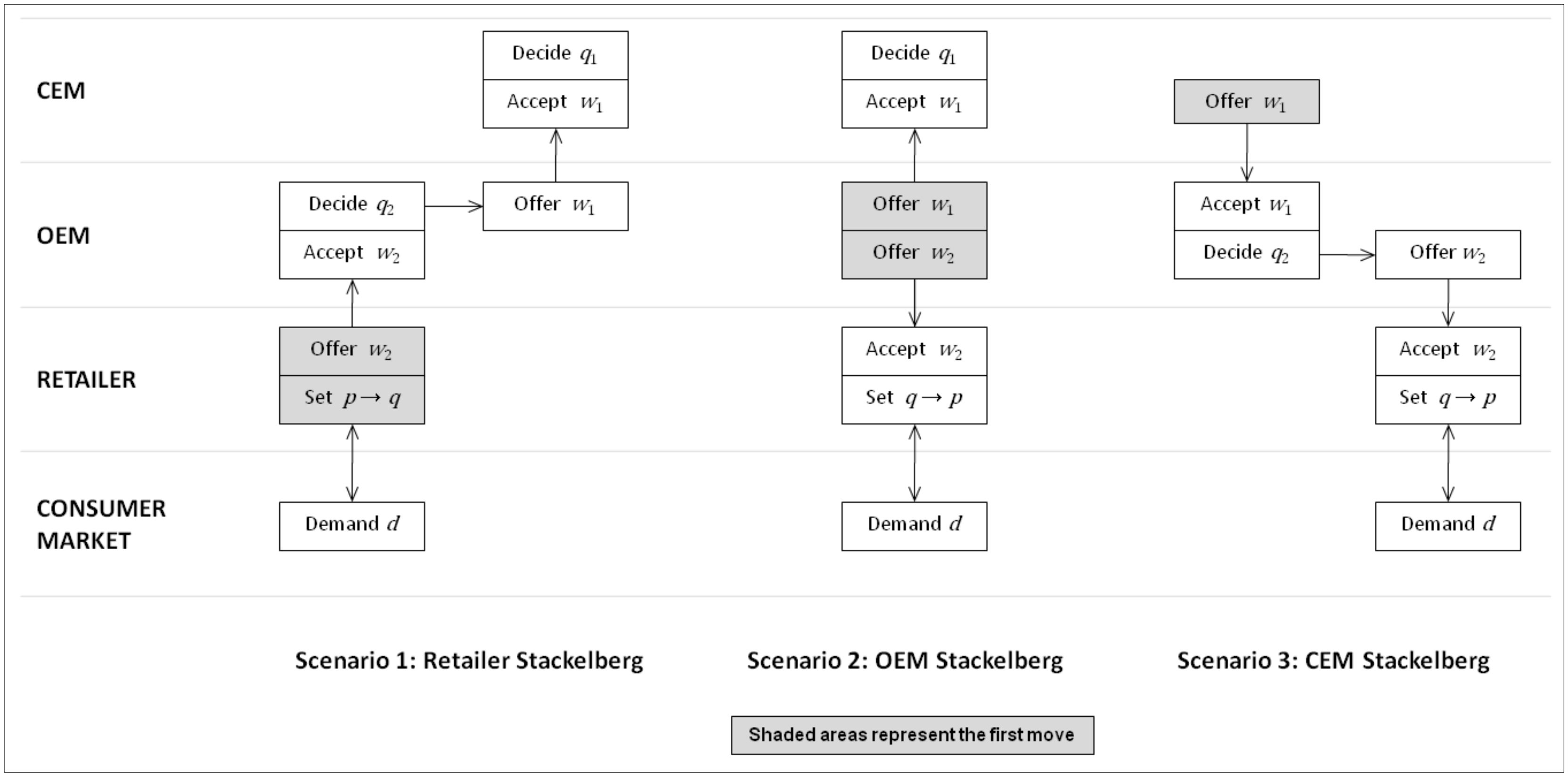

Figure 4 Decision sequential structures under different Stackelberg Leadership.

3.2 Model of a Supply Chain with Stochastic Demand Function

We also study the impact of leadership in the supply chain with stochastic consumer market demand. This situation arises where the actual market demand differs with the initial forecast. We apply a two-stage (two-period) stochastic programming with recourse model pioneered by Dantzig (1955). In this model, the decisions and constraints of the supply chain are classified into two sets. In the first period, a production plan of quantity is created based on the forecast that the consumer demand decreases linearly with price. In the second period, the actual market demand is realized. The difference between the actual market demand and the initial forecast is termed demand disruption. If , additional production needs to be planned to meet the unplanned demand . Normally this additional production requires the use of more expensive resources (for example, higher cost of overtime production and premium transportation to bring the product to the consumers). On the other hand, if the actual demand is less than the quantity produced , the supply chain may incur inventory carrying cost, order cancellation cost, etc. or may have to dispose or sell leftover inventory (in the form of final product or work-in-process) to a secondary market, usually at a lower price. In either case, the demand disruption results in changes (recourse) to the original production plan and in additional incurred costs.

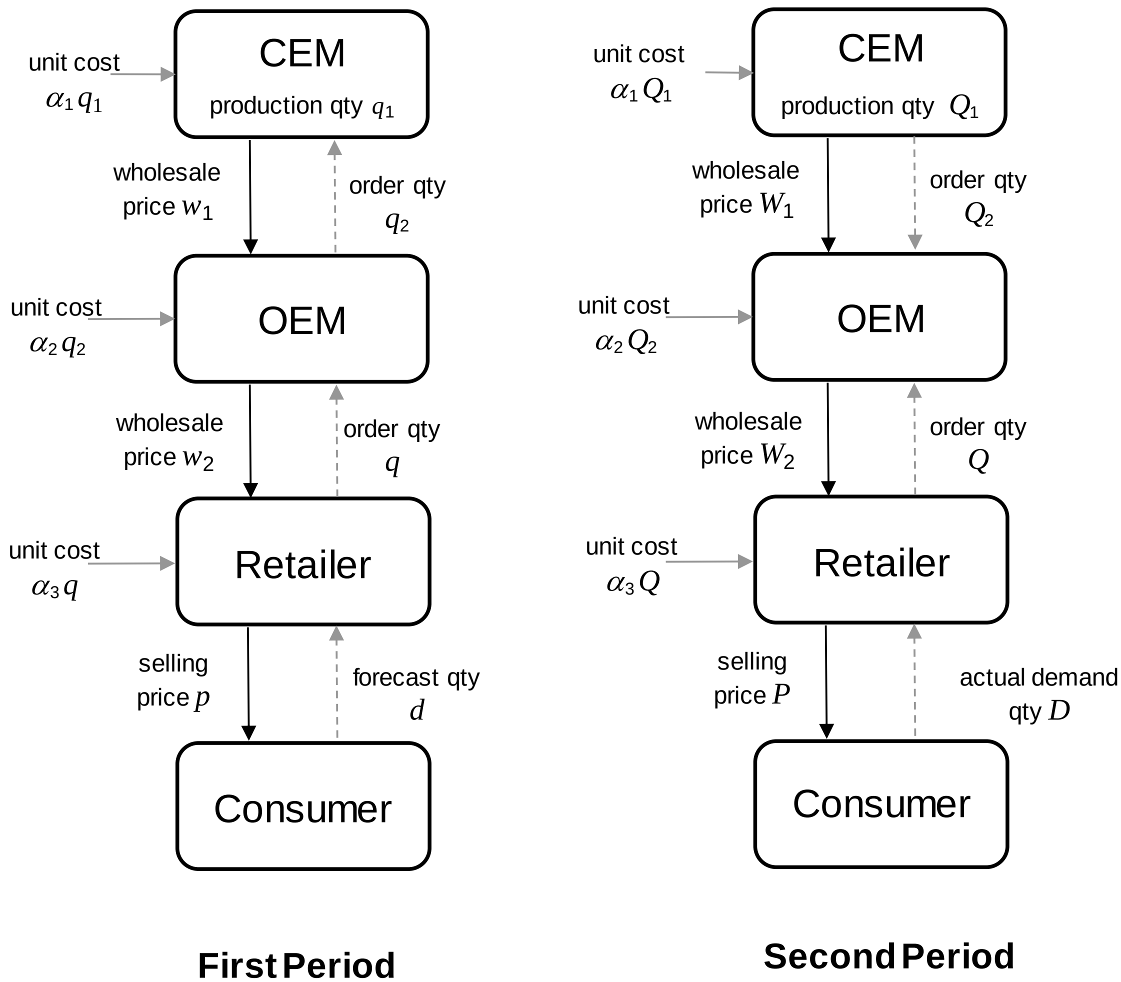

Figure 5 Decentralized supply chain model with stochastic demand function.

The actual demand quantity is different from the original forecast . The Retailer purchases from the OEM new quantity who in turn purchases from the CEM quantity . The CEM new production plan is . Since there is no quantity leftover in the supply chain, we have . We introduce and as the unit penalty cost of the increase and decrease of production from the original plan. Additional production requires more expensive resources such as overtime labor. In the case when actual demand is less than the initial plan, the supply chain may have to dispose or sell the leftover inventory to a secondary market. For simplicity, we will assume that only the Retailer carries the burden of financial risk of planning. In other words, inaccurate predictions of consumer market demand result in additional cost at the Retailer only.

The principal notations are listed in Table 2.

Table 2 Principal notation.

	No Disruption	**With Disruption**
Actual consumer demand		
Unit retail price charged to the Consumers		
Unit wholesale price to the OEM		
Unit wholesale price to the Retailer		
Quantity produced by the CEM and supplied to the OEM		
Quantity ordered by the OEM and supplied to the Retailer		
Quantity ordered by the Retailer and supplied to the market		
Profit at the CEM		
Profit at the OEM		
Profit at the Retailer		
Total Supply Chain Profit		

4. STACKELBERG LEADERSHIP IN A SUPPLY CHAIN WITH LINEAR DEMAND FUNCTION

In this section, we investigate the impact of different leadership when the consumer demand decreases linearly with price. We begin with the basic centralized firm model in section 4.1 followed by the decentralized model under different leadership in section 4.2 to 4.4. In section 4.5, we include the use of numerical approach to study the supply chain optimal decisions and profits under different leadership. We analyze the centralized supply chain as a baseline followed by the decentralized supply chain, using the changes in the supply chain profit to illustrate the effectiveness of each leadership structure. We explore how the retail price, wholesale prices, and profits are affected by changes in the leadership structure.

4.1 The Centralized Supply Chain

The linear demand function is deterministic:

(4)

Substituting with equation (4), the profit function in equation (1) now becomes:

Solving the first order condition in equation (2) will give the optimum price (and subsequently, the optimum quantity) that maximizes the centralized supply chain profit :

or, in terms of :

(5)

4.2 The Decentralized Supply Chain: Retailer Stackelberg

The Retailer sets the unit retail price and offer a contract to the OEM with unit wholesale price . The OEM accepts the contract and offers a contract to the CEM with unit wholesale price . The CEM accepts the contract and determines its production quantity . The CEM profit function is

. To maximize profit, we apply the first and second order conditions from equation (2) and (3) to the profit function:

or (6)

The OEM profit function is where is the OEM's operating cost. Substituting with equation (6) and applying conditions from equation (2) and (3), we get:

(7)

The Retailer's profit function is . Substituting with equation (7) and applying conditions from equation (2) and (3), we can calculate the optimum parameters:

(8)

The total supply chain optimum profit is the sum of the optimum profit at each supply chain member :

(9)

4.3 The Decentralized Supply Chain: OEM Stackelberg

The OEM sets the unit wholesale price contract and to maximize its profit. The CEM accepts the contract and determines its production quantity following equation (6). The Retailer accepts the contract and decides the order quantity . The profit function at the Retailer is , where is the procurement cost to the OEM and is the Retailer's operating cost. To maximize Retailer's profit, we apply the conditions from equations (2) and (3) and substitute with from equation (4):

or, (10)

The OEM profit function is . To maximize OEM's profit, we apply the conditions from equations (2) and (3) and substitute and with from equations (6) and (10):

(11)

The total supply chain optimum profit is the sum of the optimum profit at each supply chain member :

(12)

4.4 The Decentralized Supply Chain: CEM Stackelberg

The CEM offers a contract to the OEM with a unit wholesale price of . The OEM accepts the contract and in turn, offers the wholesale price to the Retailer. From equations (6) and (10), we get

Solving the first and second order condition the CEM profit function

, we obtain the optimum parameters:

(14)

The total supply chain optimum profit is the sum of the optimum profit at each supply chain member :

(15)

The optimum parameters under different leadership when the demand function is linear are tabulated in Table 3.

Table 3 Optimum parameters under different leadership when the demand function is linear expressed in .

Optimum Parameters	Centralized	Retailer Stackelberg	OEM Stackelberg	CEM Stackelberg

4.5 Numerical Analysis and Discussion: Optimal Decisions and Profits

Suppose the demand function is characterized by the market scale 10000 and the price-sensitive coefficient 1. Let the positive coefficient of the product marginal cost in the centralized supply chain is 1. The optimal demand quantity and the optimal retail price are 2500, $7500 respectively, and the maximum profit of the supply chain is $12,500,000.

In the decentralized supply chain, the positive coefficient of the marginal cost is “distributed” to each member of the supply chain. ABI Research released a report in 2007 stating that the total cost for the bill of materials can be multiplied by 2 or 2.5 in order to derive the approximate final price of cellular handset. The multiplicative factor accounts for the costs of distribution, advertising, and marketing. Based on this report, we allocate 50% of the marginal cost to the CEM, 35% to the OEM, and 15% to the Retailer, or 0.5, 0.35, and 0.15.

When the Retailer has more power in the supply chain and acts as the leader, we calculate using results from section 4.2 the optimal demand quantity = 1299 and the optimal retail price = $8701 respectively, and the maximum profit of the supply chain is = $9,613,763 or 77% of the optimum profit of the centralized supply chain. The profit distribution is as follow: at the CEM = $843,313 (9%), at the OEM = $2,276,944 (24%), and at the Retailer = $6,493,506 (68%).

Following the results from section 4.3 with the OEM as the leader, we calculate the optimal demand quantity is = 1370 and the optimal retail price is = $8630. The optimum total supply chain profit is = $9,945,581 which is 80% of the optimum profit of the centralized supply chain. The CEM profit is = $938,262, the OEM = $6,849,315 , and the Retailer = $2,158,003. We see that OEM, being the leader, experienced most of the profit (69%), followed by the Retailer (22%) and the CEM (9%).

When CEM is the leader, we find using results from section 4.4 that the optimal demand quantity and the optimal retail price are 862 and $9138 respectively. The optimum total supply chain profit is $7,134,364. Let be the coefficient of efficiency of the decentralized supply chain, as defined by

——. Substituting the profit values, we know that the efficiency of the CEM-led supply chain is 57% of the centralized supply chain with the same demand parameters. At the CEM, the profit is $4,310,345 , the OEM $1,969,382 , and the Retailer $854,637. We see that CEM, being the leader, experienced most of the profit (60%) followed by the OEM (28%) and the Retailer (12%).

The results above are tabulated in table 4 and are consistent with the observation that most decentralized supply chains derive less profit than their corresponding centralized supply chain. The supply chain leader experienced the most of the profit, followed by the next upstream/downstream member of the supply chain. The leadership structure in the decentralized supply chain has a significant impact on the retail price. While the end consumer must spend much more in the CEM-led model, the total supply chain profit is actually the least relative to the OEM- and Retailer-led model. The profit efficiency in the OEM Stackelberg is slightly higher than the Retailer Stackelberg. The end consumer may not notice the difference of the supply chain leadership structure because the two retail prices are very close. Compared to the centralized supply chain as the baseline, the lowest retail price (in the OEM Stackelberg) is 15% higher, and the highest retail price (in the CEM Stackelberg) is 22% higher.

Table 4 Effect of different leadership structure on optimum parameters and profits in the supply chain with linear demand function.

	Centralized	Decentralized		
		CEM leads	OEM leads	Retailer leads
	2500	862	1370	1299
		$5431	$1370	$1299
		$8017	$6849	$3506
	$7500	$9138	$8630	$8701
		$4,310,345 (60%)	$938,262 (9%)	$843,313 (9%)
		$1,969,382 (28%)	$6,849,315 (69%)	$2,276,944 (24%)
		$854,637 (12%)	$2,158,003 (22%)	$6,493,506 (68%)
	$12,500,000	$7,134,364	$9,945,581	$9,613,763
η	100%	57%	80%	77%

4.6 Numerical Analysis and Discussion: Effect of Cost Distribution on Optimum Profit under Different Leadership

We normalize the cost coefficient such that = 1. The cost coefficient now represents the cost distribution between CEM, OEM, and Retailer respectively. For practical purpose, we assume that the unit cost at CEM cannot be less than 5% of the total cost, or 0.05. We investigate two extreme cases:

- 0, meaning that the unit cost at the OEM is insignificant relative to the unit cost at the CEM and Retailer. Example of this case is where the finish products are shipped directly from the CEM to the Retailer (direct fulfillment mode) and the Retailer bears all the marketing expenses.
- 0, meaning that the unit cost at the Retailer is insignificant relative to the unit cost at the CEM and OEM. Example of this case is where the OEM subsidized the marketing expenses of the Retailer.

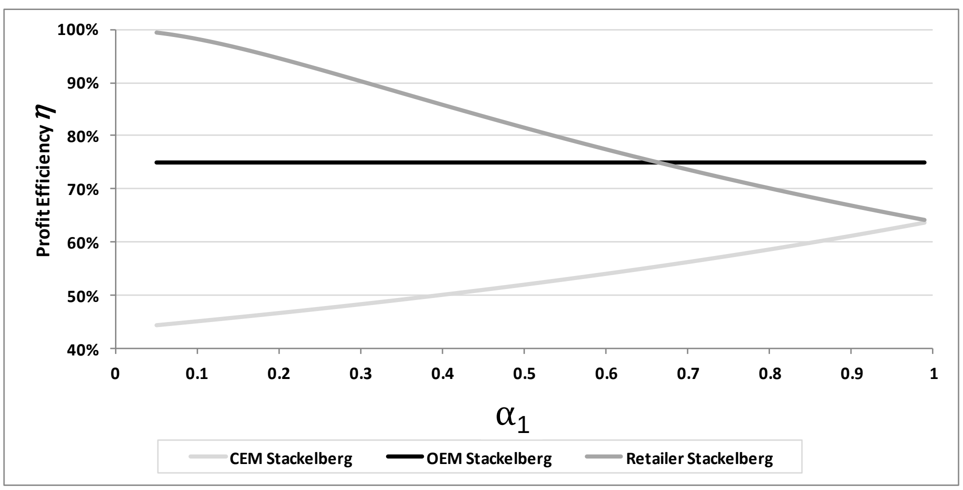

Figure 6 Effect of increasing CEM's marginal cost coefficient on the profit efficiency under different leadership with linear demand function, where the unit cost is allocated to CEM and Retailer only.

From Figure 6, we see that when all the costs are allocated to the CEM and the Retailer only, the optimum profit in the OEM Stackelberg supply chain is not affected by the increasing unit cost at the CEM (and decreasing unit cost at the

Retailer). The optimum profit in CEM Stackelberg supply chain increases linearly but still lower than the optimum profit in OEM Stackelberg. The maximum profit efficiency is 99.51% in Retailer Stackelberg supply chain when the CEM unit cost is at its minimum (= 0.05) and the Retailer unit cost is at its maximum (= 0.95). The Retailer Stackelberg's optimum profit decreases linearly as increases (decreases) at a rate faster than the rate of increase of the optimum profit of the CEM Stackelberg. The optimum profit of the OEM and Retailer Stackelberg intersects at = 0.667 (75% efficiency), which means that the maximum profit efficiency is 75% regardless of whether the OEM or the Retailer leads when the CEM bears 2/3 of the total unit cost.

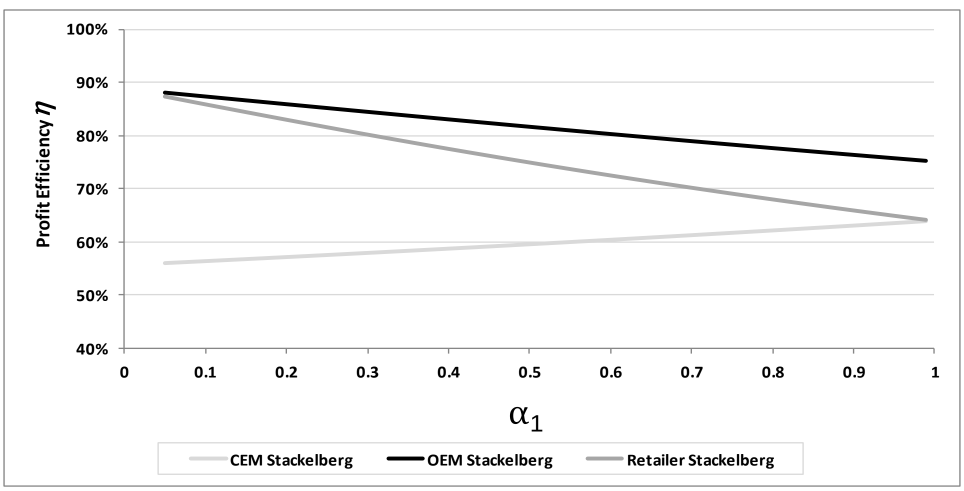

Figure 7 Effect of increasing CEM's marginal cost coefficient on the profit efficiency under different leadership with linear demand function, where the unit cost is allocated to CEM and OEM only.

From Figure 7, we see that when all the costs are allocated to the CEM and the OEM only, the optimum profit in the OEM and Retailer Stackelberg supply chain decrease linearly with the increasing unit cost at the CEM (and decreasing unit cost at the Retailer); the rate of the decrease is higher in the Retailer Stackelberg. The optimum profit in the CEM Stackelberg supply chain increases linearly but still lower than the optimum profit in the OEM and Retailer Stackelberg. The maximum profit efficiency of 88.15% is achieved when the OEM is the leader and the CEM cost is at its minimum (= 0.05) and the OEM cost is at its maximum (= 0.95).

Figure 8 shows the leadership that will achieve highest optimum profit efficiency in our model. The Retailer Stackelberg supply chain has the most optimum profit efficiency when the unit cost is allocated to the CEM and the Retailer only (= 1; = 0) up until the CEM unit cost is at 50% (at this point, = 0.5). When the CEM unit cost is more than 50% of the overall unit cost, the highest optimum profit efficiency is achieved when the powerful OEM leads the supply chain and the unit cost is allocated to the CEM and the OEM only (= 1; = 0).

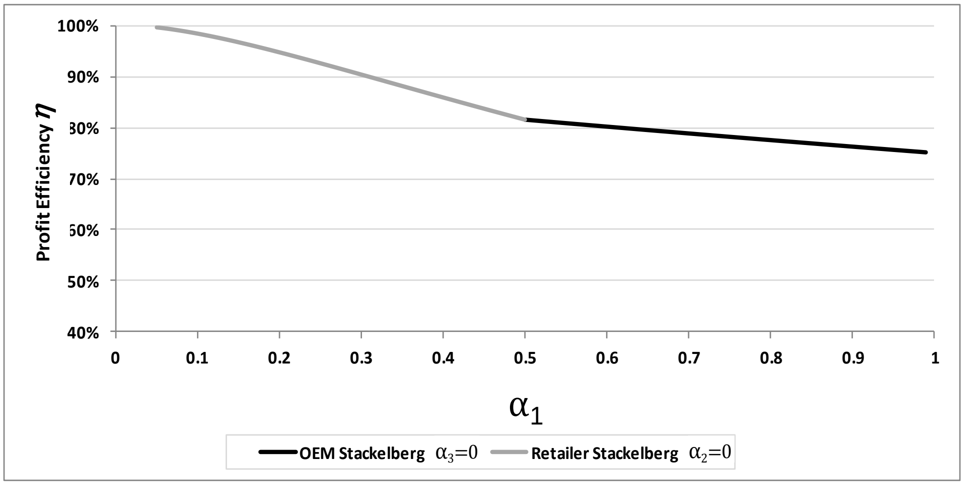

Figure 8 The highest optimum profit efficiency of the supply chain with linear demand function.

4.7 Numerical Analysis and Discussion: Effect of Cost Distribution on Supply Chain Member's Profit under Different Leadership

We investigate the effect of the unit cost to the profit distribution of the supply chain members. We plot in Figure 9 the profit distribution in the CEM Stackelberg supply chain relative to the CEM unit cost. The CEM profit is at its lowest (57%-60%) when its unit cost is 5% of the overall supply chain unit cost. The CEM profit rises slightly when more of the supply chain cost is absorbed by the CEM, reaching its maximum at 60% of the total supply chain profit when all unit cost is allocated to the CEM. The OEM profit is higher than the Retailer regardless of the unit cost distribution.

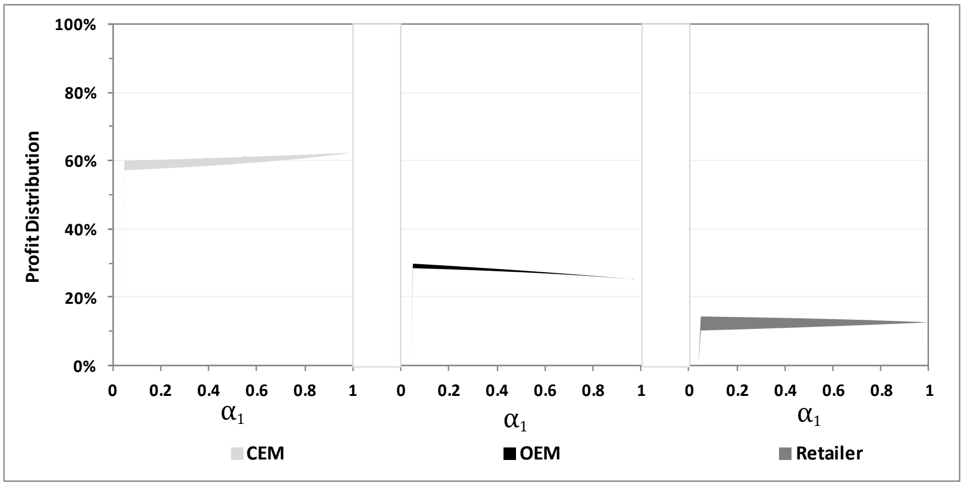

Figure 9 Effect of CEM unit cost to the profit distribution in a CEM Stackelberg supply chain with linear demand function.

In Figure 10, we plot the profit distribution in the OEM Stackelberg relative to the OEM unit cost. The lowest OEM profit is at 67% of the total supply chain profit when the unit cost is shared only by the CEM and the Retailer. The OEM profit increases as more of the unit cost is absorbed, reaching its maximum at 74%. The OEM profit share is not affected by how the unit cost is distributed between the CEM and the Retailer. The Retailer profit is significantly higher than the CEM.

The profit distribution in the Retailer Stackelberg relative to the Retailer unit cost is shown in Figure 11. The lowest Retailer profit is at 63%-74% of the total supply chain profit when the unit cost is shared by the CEM and the OEM and it increases as the Retailer absorbs more of the unit cost, reaching its maximum at 93%.

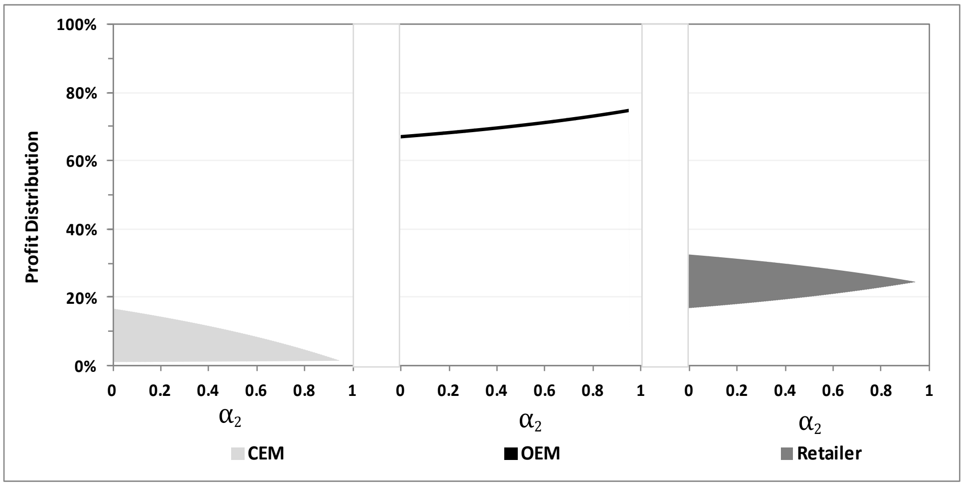

Figure 10 Effect of OEM unit cost to the profit distribution in an OEM Stackelberg supply chain with linear demand function.

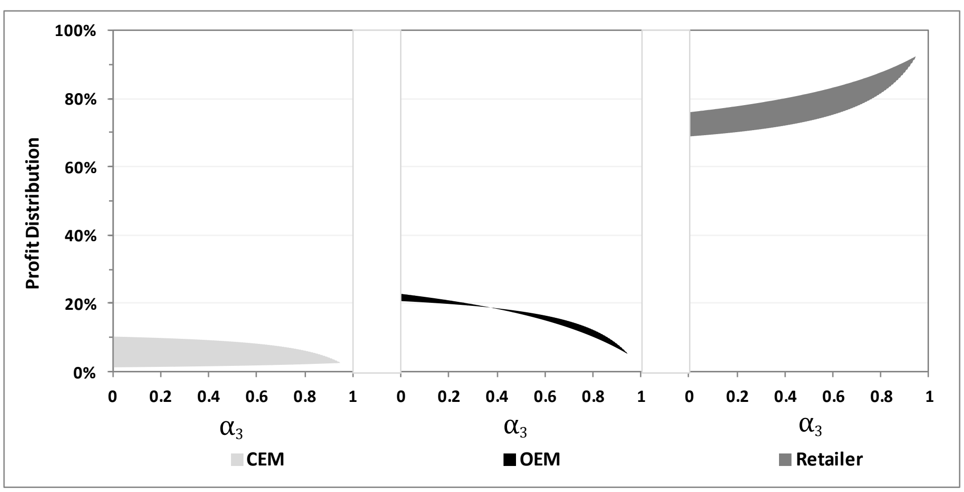

Figure 11 Effect of Retailer unit cost to the profit distribution in a Retailer Stackelberg supply chain with linear demand function.

5. STACKELBERG LEADERSHIP IN A SUPPLY CHAIN WITH EXPONENTIAL DEMAND FUNCTION

Using the same methodologies as in section 4, we obtain the optimum parameters under different leadership when the demand function is exponential. The results are tabulated in Table 5.

5.1 Numerical Analysis and Discussion: Optimal Decisions and Profits

Suppose the demand function is characterized by the market scale and the price-sensitive coefficient Let the positive coefficient of the product marginal cost in the centralized supply chain is . The optimal demand quantity and the optimal retail price are = $3056 respectively, and the maximum profit of the supply chain is = $2,189,267.

Table 5 Optimum parameters under different leadership when the demand function is exponential expressed in .

Opt. Para.	Centralized	Retailer Stackelberg	OEM Stackelberg	CEM Stackelberg

As in the previous section for the decentralized supply chain, we allocate 50% of the marginal cost to the CEM, 35% to the OEM, and 15% to the Retailer, or and . We calculate the optimum profit under different leadership by using the formula from table 5 and the results are tabulated in table below.

Table 6 Effect of different leadership structure on optimum parameters and profits in the supply chain with exponential demand function.

	Centralized	**Decentralized**		
		CEM leads	**OEM leads**	**Retailer leads**
	1146	451	609	495
		$1582	$610	$496
		$2757	$2501	$1339
	$3056	$3857	$3578	$3768
		$612,817 (40%)	$186,013 (10%)	$122,932 (8%)
		$459,613 (30%)	$1,023,073 (57%)	$331,919 (20%)
		$466,422 (30%)	$601,443 (33%)	$1,167,863 (72%)
	$2,189,267	$1,538,853	$1,810,528	$1,622,715
η	100%	70%	83%	74%

The leadership structure in the decentralized supply chain with exponential demand has a more significant impact on the retail price than the one with linear demand. In the example above, the lowest retail price (in the OEM Stackelberg) is 17% higher, and the highest retail price (in the CEM Stackelberg) is 26%

higher. This is 2-4 points higher than the decentralized supply chain with linear demand. While the end consumer must spend more in the CEM-led model, the total supply chain profit is actually the least relative to the OEM- and Retailer-led model. The profit efficiency in the OEM Stackelberg is the highest, even though the retail price is the lowest among the three different leadership structures.

5.2 Numerical Analysis and Discussion: Effect of Cost Distribution on Optimum Profit under Different Leadership

When all the costs are allocated to the CEM and the Retailer only, the optimum profit in the OEM Stackelberg supply chain is not affected by the increasing unit cost at the CEM (and decreasing unit cost at the Retailer). The optimum profit in CEM Stackelberg supply chain increases exponentially and surpasses the optimum profit in OEM Stackelberg when 84% of the unit cost is absorbed by the CEM. The maximum profit efficiency is 99.15% in Retailer Stackelberg supply chain when the CEM cost is at its minimum , and the Retailer cost is at its maximum . The Retailer Stackelberg's optimum profit decreases exponentially as increases (decreases) at a similar rate with the rate of increase of the optimum profit of the CEM Stackelberg. The optimum profit of the OEM and Retailer Stackelberg intersects at (76% efficiency), which means that the maximum profit efficiency is 76% regardless of whether the OEM or the Retailer leads when the CEM bears ~57% of the total unit cost. Figure 11 shows the effect of CEM unit cost on the supply chain profit efficiency under different leadership when the OEM does not carry any unit cost.

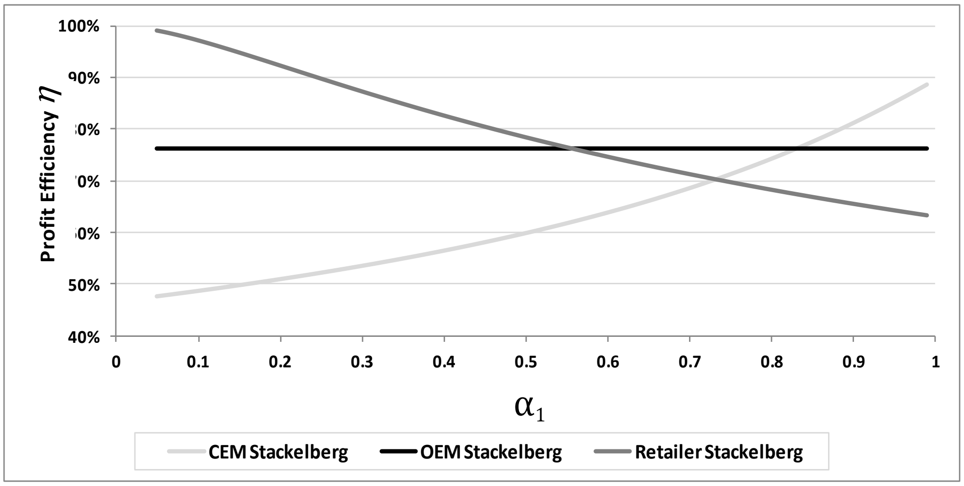

Figure 12 Effect of increasing CEM's marginal cost coefficient on the profit efficiency under different leadership with exponential demand function, where the unit cost is allocated to CEM and Retailer only.

When all the costs are allocated to the CEM and the OEM only, the optimum profit in the OEM and Retailer Stackelberg supply chain decrease exponentially with the increasing unit cost at the CEM (and decreasing unit cost at the Retailer); the rate of the decrease is slightly higher in the Retailer Stackelberg. The optimum profit in the CEM Stackelberg supply chain increases exponentially and becomes the highest when 72% of the total unit cost is absorbed by the CEM ( ). The maximum profit efficiency of 95.73% is achieved when the OEM is the leader and the CEM cost is at its minimum and the OEM cost is at its maximum . Figure 13 shows the effect of CEM unit cost on the supply chain profit efficiency under different leadership when the Retailer does not carry any unit cost.

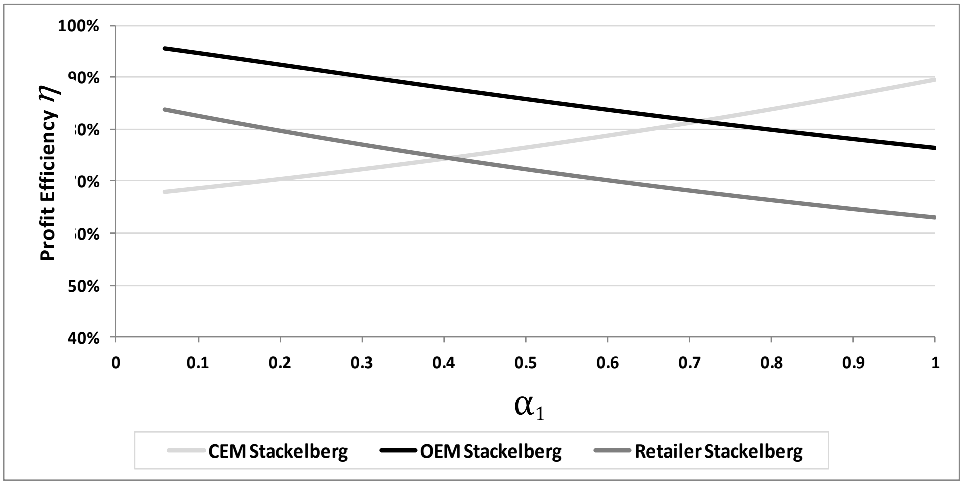

Figure 13 Effect of increasing CEM's marginal cost coefficient on the profit efficiency under different leadership with exponential demand function, where the unit cost is allocated to CEM and OEM only.

The highest optimum profit efficiency in our model is shown in Figure 14. The Retailer Stackelberg supply chain has the most optimum profit efficiency when the unit cost is allocated to the CEM and the Retailer only

, up until the CEM unit cost is at 20% (at this point,).

When the CEM unit cost is more than 20% but less than 71% of the overall unit cost, the highest optimum profit efficiency is achieved when the powerful OEM leads the supply chain. When the unit cost is more than 71% at the CEM, the CEM Stackelberg supply chain will have the highest optimum profit provided that there is no unit cost at the Retailer.

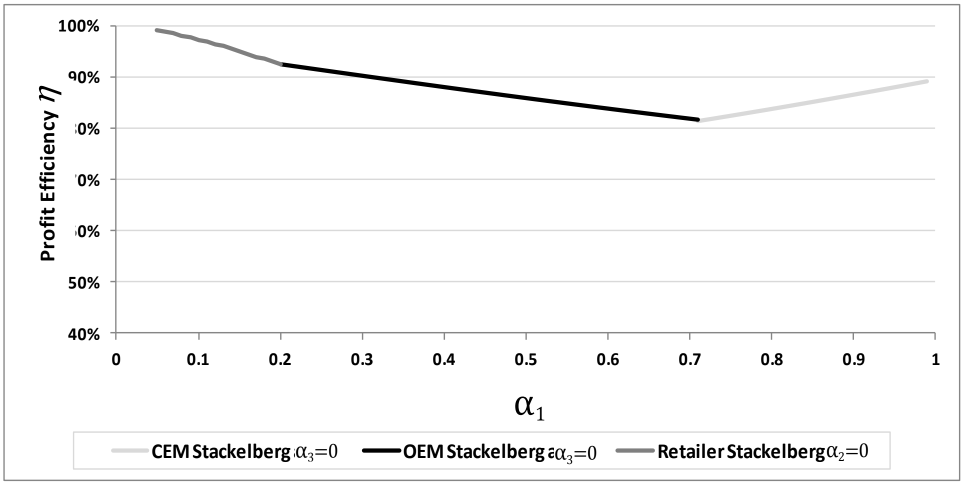

Figure 14 The highest optimum profit efficiency of the supply chain with exponential demand function.

5.3 Numerical Analysis and Discussion: Effect of Cost Distribution on Supply Chain Member's Profit under Different Leadership

We now investigate the effect of the unit cost to the profit distribution of the supply chain members. We plot in Figure 15 the profit distribution in the CEM Stackelberg supply chain relative to the CEM unit cost. The CEM profit is at its lowest (~37%) when its unit cost is 5% of the overall supply chain unit cost and rises when more of the supply chain cost is absorbed by the CEM, reaching its maximum at ~45% of the total supply chain profit when all unit cost is allocated to the CEM. Unlike in the Liner Demand situation, the OEM profit may be lower than the Retailer depending on the unit cost contribution up when the unit cost at the

CEM accounts up to 58% of the total. When the CEM unit cost is 58% or more of the total unit cost, the OEM profit is lower than the Retailer.

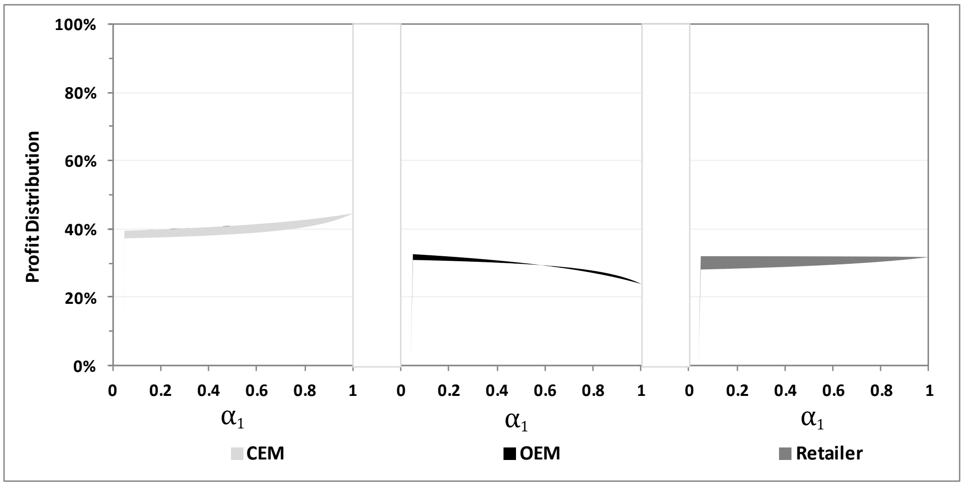

Figure 15 Effect of CEM unit cost to the profit distribution of each member in a CEM Stackelberg supply chain with exponential demand function.

We plot the profit distribution in the OEM Stackelberg relative to the OEM unit cost In Figure 16. The lowest OEM profit is at 55% of the total supply chain profit when the unit cost is shared by the CEM and the Retailer. Similar to the Linear Demand situation, the OEM profit increases as more of the unit cost is absorbed, reaching its maximum at 64%. The OEM profit share is not affected by how the unit cost is distributed between the CEM and the Retailer. The Retailer profit is significantly higher than the CEM.

The profit distribution in the Retailer Stackelberg relative to the Retailer unit cost is shown in Figure 17. The lowest Retailer profit is at 69-76% of the total supply chain profit when the unit cost is shared by the CEM and the OEM and it increases as the Retailer absorbs more of the unit cost, reaching its maximum at

93%. The profit distribution profile of the Retailer Stackelberg supply chain with exponential demand is almost identical to the one with linear demand in Figure 11.

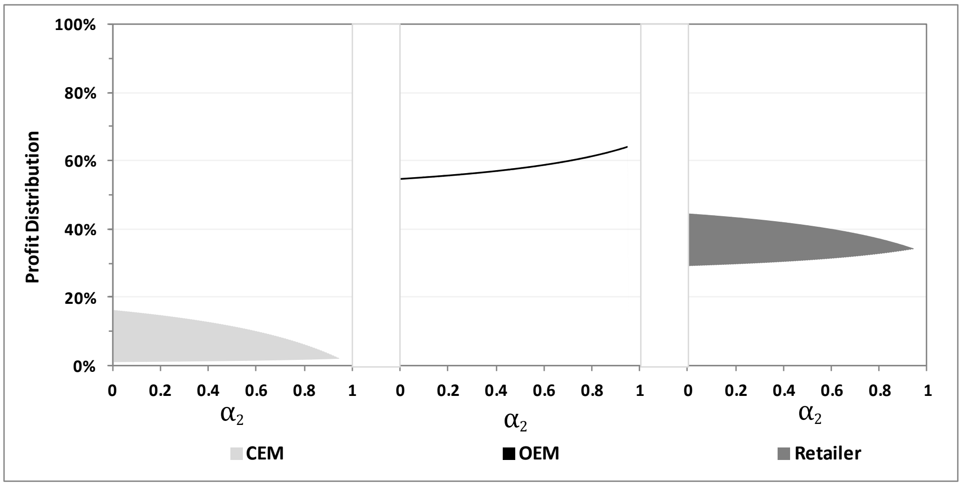

Figure 16 Effect of OEM unit cost to the profit distribution of each member in an OEM Stackelberg supply chain with exponential demand function.

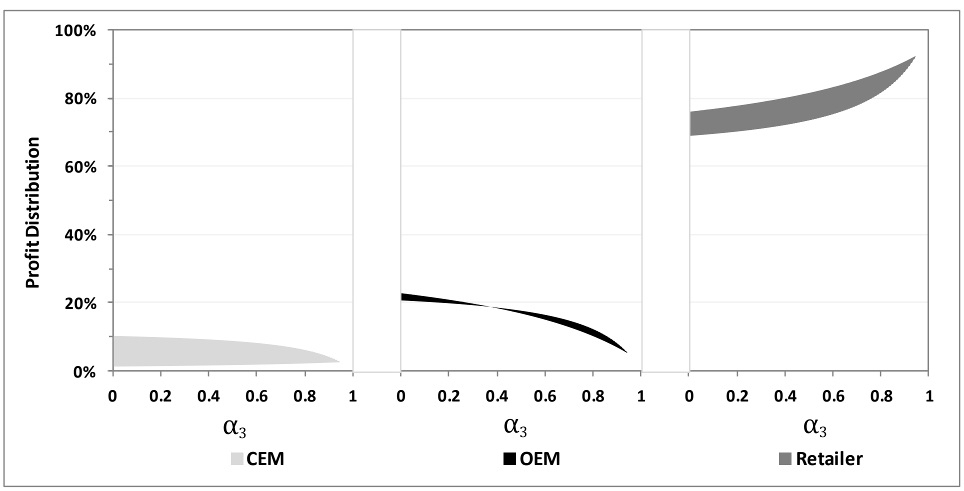

Figure 17 Effect of Retailer unit cost to the profit distribution in a Retailer Stackelberg supply chain with exponential demand function.

6. STACKELBERG LEADERSHIP IN A SUPPLY CHAIN WITH STOCHASTIC DEMAND FUNCTION

The linear and exponential demand functions in sections 4 and 5 assume that the supply chain has perfect information about the consumer demand. However, perfect market information is rarely available in practice. In this section, we investigate the impact of different leadership when the consumer demand is stochastic using the two-stage stochastic programming with recourse model. The randomness in demand is price independent and can be modeled in an additive form (Mills 1959). In the first period, the production plan is created based on the demand forecast . The actual demand realized in the second period is :

(16)

where is assumed to be a normally distributed random variable.

represents an increased market demand, and represents a decreased market demand. The Retailer purchases from the OEM quantity at unit wholesale price , and sells to the consumer at a new retail price . The CEM produces quantity and sells to the OEM at unit wholesale price . Since there is no quantity leftover in the supply chain, we have . We introduce and as the unit penalty cost of the increase and decrease of production from the original plan. We begin with the basic centralized firm model in section 6.1 followed by the decentralized model under different leadership in section 6.2 to 6.4.

6.1 The Centralized Supply Chain with Stochastic Demand Function

The new retail price from the actual market demand in equation (16) can be written as

The centralized supply chain optimization problem now becomes

where is the new total supply chain profit and .

We propose two constraints:

- when : the production quantity cannot be decreased when the actual demand is more than originally planned.

- when : the production quantity cannot be increased when the actual demand is less than originally planned.

6.1.1 Actual demand is more than originally planned ( )

Since or , the centralized supply chain profit function (18) now becomes

We calculate the new optimum quantity using the first order condition as in equation (2) and compare with the original optimum quantity from equation (5):

We proposed earlier the constraint when , but we see that will be less than if . We have two cases with regard to the value of in equation (20):

Case 1:

When this condition is true, satisfies the constraint when ,

implying that is indeed maximized at . We calculate the new optimum retail price from equation (17) and the maximum profit of the centralized supply chain from equation (19), and compare with the optimum solution in the linear demand function in equation (5):

The increase in the consumer demand results in the optimum solution that is higher than the original one.

Case 2:

When this condition is true, does not satisfy the constraint when , implying that is indeed maximized at . This implies that the original production plan should not be changed unless the magnitude of demand disruption is large enough (greater than). However, the retail price can be increased following the new demand function. We calculate the new optimum retail price from equation (17) and the maximum profit of the centralized supply chain from equation (19), and compare with the optimum solution in equation (5):

Although the quantity sold is the same as the originally planned, the retail price can be increased and hence, the profit will increase as well.

6.1.2 Actual demand is less than originally planned ( )

Since or , the centralized supply chain profit function (18) now becomes

We calculate the new optimum quantity using the first order condition as in equation (2) and compare with the original optimum quantity from equation (5):

Similar to section 6.1.1, we see that the value of may be greater than if . We have two cases with regard to the additive term in equation (24):

Case 3:

When this condition is true, does not satisfy the constraint when . This implies that the original production plan should not be changed unless the magnitude of demand disruption is large enough (greater than). The optimum solution of case 3 is exactly the same as case 2 equation (22). The quantity sold is the same as the originally planned but the retail price should be decreased to achieve maximum profit (which is still less than the optimum profit in the linear demand function).

Case 4:

When this condition is true, satisfies the constraint when , implying that is indeed maximized at . We calculate the new optimum retail price from equation (17) and the maximum profit of the centralized supply chain from equation (19), and compare with the optimum solution in equation (5):

The decrease in the consumer demand results in the optimum solution that is lower than the original one.

6.2 The Decentralized Supply Chain with Stochastic Demand Function

We consider a decentralized supply chain with OEM as the leader. Applying the actual demand from equation (16) and the new retail price from equation (17), the profit maximization problem at the Retailer in equation (18) now becomes

where (26)

.

We apply the same two constraints as were given earlier for the centralized supply chain in section 6.1.

6.2.1. Actual demand is more than originally planned ( )

Since or , the Retailer's profit maximization function (26) now becomes s.t.

We can rewrite equation (28) in terms of from equation (11):

Equation (29) shows that constraint alone is not sufficient, because it does not guarantee that . We will now investigate two cases, as before.

Case 1:

When this condition is true, satisfies the constraint .

Following the similar procedure as in the case of the decentralized model with no demand disruptions, we have the following optimum solutions:

Using this result, the constraint also can be written as .

Case 2: or

When this condition is true, does not satisfy the constraint . There is no feasible solution for equation (27). The original production plan should not be increased ( ) and all other CEM and OEM optimum parameters are the same as in the decentralized model with no demand disruption – see equations (6), (10), and (11). On the other hand, the Retailer always has a chance to increase the retail price as long as it satisfies the linear demand function in equation (16). The new retail price is

and the supply chain new profit is

The constraint also can be written as

.

6.2.2 Actual demand is less than originally planned ( )

Since or , the Retailer's profit maximization function (26) now becomes

s.t.

or, in terms of from equation (11):

Equation (35) shows that constraint alone is not sufficient, because it does not guarantee that . Similar to section 6.1, we investigate two cases:

Case 3:

When this condition is true, does not satisfy the constraint . There is no feasible solution for equation (33). The original production plan should not be decreased ( ). However, unlike in case 2, the value of is negative. The Retailer has to lower the retail price to avoid the penalty cost of disposing the leftover quantity.

The constraint also can be written as

.

Case 4:

When this condition is true, satisfies the constraint .

Following the similar procedure as in the case of the decentralized model with no demand disruptions, we have the following optimum solutions:

The constraint can also be written as

.

Using the same method as above, we can generalize the results for CEM Stackelberg and Retailer Stackelberg as follows:

Table 7 Four different cases in stochastic demand function where i = Retailer Stackelberg, OEM Stackelberg, CEM Stackelberg and ,

Optimum Parameters	Case 1	Case 2	Case 3	Case 4
		—	—	
		—	—	
		—	—	

6.3 Numerical Analysis and Discussion: Optimal Decisions and Profits

Suppose the demand function is characterized by the market scale the price-sensitive coefficient the positive coefficient of the product marginal cost in the centralized supply chain , and and as the unit penalty cost of the increase and decrease of production from the original plan respectively. The penalty cost for disposing leftover quantities is less than the penalty cost for producing more because we assume that the leftover product still can be sold to the market but at a much lower price. As in the previous section for the decentralized supply chain, we allocate 50% of the marginal cost to the CEM, 35% to the OEM, and 15% to the Retailer, or and . Using the results from Table 7, we calculate the optimum profit under different leadership for the four possible cases, with for case 1, for case 2, - for case 3, and - for case 4. The results are tabulated below.

Table 8 Effect of different leadership structure on optimum parameters and profits in the supply chain with stochastic demand function: case 1.

	Centralized	Decentralized		
		CEM leads	OEM leads	Retailer leads
	2525	870	1383	1311
		$5485	$1384	$1312
		$8097	$6918	$3542
	$7875	$9529	$9016	$9088
		$4,396,983 (58%)	$957,121 (9%)	$860,263 (8%)
		$2,008,966 (27%)	$6,986,986 (66%)	$2,322,710 (23%)
		$1,130,436 (15%)	$2,612,338 (25%)	$7,013,636 (69%)
	$13,501,250	$7,536,385	$10,556,446	$10,196,610
η	100%	56%	78%	76%

Table 9 Effect of different leadership structure on optimum parameters and profits in the supply chain with stochastic demand function: case 2.

	Centralized	Decentralized		
		CEM leads	OEM leads	Retailer leads
	2500	862	1370	1299
		$5431	$1370	$1299
		$8017	$6849	$3506
	$7600	$9238	$8730	$8801
		$4,310,345 (60%)	$938,262 (9%)	$843,313 (9%)
		$1,969,382 (27%)	$6,849,315 (68%)	$2,276,944 (23%)
		$940,844 (13%)	$2,249,990 (23%)	$6,623,377 (68%)
	$12,750,000	$7,220,571	$10,082,567	$9,743,633
η	100%	57%	79%	76%

Table 10 Effect of different leadership structure on optimum parameters and profits in the supply chain with stochastic demand function: case 3.

	Centralized	Decentralized		
		CEM leads	**OEM leads**	**Retailer leads**
	2500	862	1370	1299
		$5431	$1370	$1299
		$8017	$6849	$3506
	$7400	$9038	$8530	$8601
		$4,310,345 (61%)	$938,262 (10%)	$843,313 (9%)
		$1,969,382 (28%)	$6,849,315 (70%)	$2,276,944 (24%)
		$768,430 (11%)	$2,021,017 (21%)	$6,363,636 (67%)
	$12,250,000	$7,048,157	$9,808,594	$9,483,893
	100%	58%	80%	77%

Table 11 Effect of different leadership structure on optimum parameters and profits in the supply chain with stochastic demand function: case 4.

	Centralized	Decentralized		
		CEM leads	**OEM leads**	**Retailer leads**
	2475	853	1356	1285
		$5377	$1356	$1286
		$7937	$6781	$3471
	$7275	$8897	$8394	$8464
		$4,224,569 (62%)	$919,591 (10%)	$826,531 (9%)
		$1,930,191 (28%)	$6,713,014 (70%)	$2,231,633 (24%)
		$708,320 (10%)	$1,909,580 (20%)	$6,169,481 (67%)
	$11,876,250	$6,863,080	$9,542,184	$9,227,644
η	100%	58%	80%	78%

In all four cases, we see that the OEM Stackelberg retains its highest optimum profit efficiency, just like in the original linear demand function case (Table 4). The impact of demand randomness to the optimum overall supply chain profit efficiency under different leadership structures is minimal in our example.

7. DEMAND DISRUPTION MANAGEMENT

In this section, we investigate the supply chain that experiences a demand disruption that results in an inevitable deviation from the initial production plan. When actual consumer demand is higher than the forecast (positive disruption), overtime production and expedited delivery are required. On the other hand, when actual demand is lower than the forecast (negative disruption), costs for holding excess inventory and perhaps disposal are incurred. If not managed properly and timely, such deviations will severely affect the firms' performance in terms of revenue, operational efficiency, consumer satisfaction, and market competitiveness.

Disruption management is concerned with analyzing the costs of deviating from existing production plans. Our objective is to determine how to retain the supply chain profit by making adjustments to the production plan in the second period once the demand is realized. We try to maintain the original production plan as much as possible, because in practice, there are many significant implicit costs that are involved when the original plan cannot be carried out. These implicit costs are not represented in our simplistic model because they are difficult to quantify.

We measure the effectiveness of demand disruption management through the changes in the supply chain profit. We analyze the penalty cost incurred when the actual demand deviates from the original production plan. We will reuse the supply chain model facing stochastic demand function from section 6. We consider the randomness in demand in equation (16) as the disruption to the base demand, which is deterministic and decreases linearly in price. We extend our study on disruption management to include the exponential demand function as the base demand. However, we are not able to derive the exact solutions analytically as in section 6.1 and 6.2 because the math becomes substantially complicated. We will adopt a numerical analysis approach and present this in section 7.3 and 7.4.

As a baseline, we consider the production plan in the second period equals to the plan in the first period and the retail price remains the same. We take into account the consequence of not responding to the demand disruption (e.g., some quantities will be left unsold when the actual demand is less than the original plan). We apply the methods of handling the demand disruption that will generate the optimum profit from section 6. In the centralized model, the firm will adjust both production plan and the retail price if the disruption is major (beyond a certain threshold) and otherwise only will adjust the retail price. In the decentralized model, the OEM, being the leader, will make adjustment to the production plan and the wholesale price policies only when the demand disruption is major (beyond a certain threshold). When the demand disruption is minor, the OEM will keep the original production plan and the wholesale price policies and let the Retailer make a decision on the retail price. We label these methods as Optimum Disruption Management. We also investigate the situation where the Retailer sets the retail price independently in order to maximize own profit. We show that this retail price adjustment method works well only when the disruption is positive. We use the same penalty cost for changing the production plan due to the demand increase and due to the demand decrease when the base demand function is linear as well as exponential.

7.1 Numerical Analysis and Discussion on Disruption to the Base Linear Demand in a Centralized Supply Chain

Let the demand function is characterized by the market scale the price-sensitive coefficient the positive coefficient of the product marginal cost in the centralized supply chain . The optimal demand quantity is , the optimal retail price is , and the supply chain profit will be . These are the baseline parameters.

Case 1: Demand Increase ( )

Suppose the market scale is higher than anticipated, . In the baseline case, the demand increase is completely ignored. There are no changes in the production quantity, the retail price, and the profit. However, from equation (4) and (16), we can see that there is an opportunity to increase the retail price to $1100.

The profit now becomes

- = $225,000.

This is an increase of 80% compared to the profit from the original production plan.

Also from equation (4) and (16), we see that the firm has the option to sell more quantity with the original retail price. However, when the production plan is increased, the firm will lose money due to the penalty cost . With the numbers above, the firm profit goes to zero when the production quantity is increased to 450 units.

Within the demand disruption context, this situation corresponds to case 1 in section 6.1.1 . From equation (20), we get the new optimal retail price , the new production quantity is , and the new supply chain profit is . By acting upon the demand disruption, more quantity will be sold at a higher retail price and the profit will increase by 81%.

From the results above, we see that the Optimum Disruption Management method in case 1 will generate more profit rather than no action at all. The difference in the profit increase between the retail price adjustment and the Optimum Disruption Management method is small (1%) when the market scale increases by 40%, but it grows larger with the higher market scale increase. For example, the Optimum Disruption Management method will result in 49% incremental profit compare to the retail price adjustment when the market scale increases by 100%.

Case 2: Demand Increase)

Suppose the market scale increase is 100, which corresponds to case 2 in section 6.1.1. This demand increase is ignored in the baseline case. Applying the Optimum Disruption Management, the owner retains the original production plan of 250 units but increases the retail price to $850. This results in a profit of $150,000, an increase of 20% from the baseline. The Optimum Disruption Management method is in fact the same with the retail price adjustment method in this case.

Case 3 Demand Decrease

The market scale decreases by 50, which corresponds to case 3 (

) in section 6.1.2. When the demand decrease is ignored (baseline), only 200 units can be sold at $750 unit price. The profit will be $84,500 after $3000 penalty cost for disposing 50 leftover units.

Applying the Optimum Disruption Management, the firm keeps the original production plan of 250 units but has to reduce the retail price to $700 to avoid any leftover. This results in $112,500 profit, an increase of 33% from the baseline. Similar with case 2, the Optimum Disruption Management method in case 3 is in fact the same with the retail price adjustment method.

Case 4 Demand Decrease

Suppose the market scale now is lower than anticipated, . As the baseline, we consider the firm continues to product 250 units and to sell at the $750 retail price. At the end of the second period, there are 100 units left over. The profit is $44,000 after incurring a $6000 penalty cost of disposing the 100 excess units.

If the firm chooses to sell all of 250 units per the original production plan and to lower the unit retail price to $650 per equation (4), the maximum profit will be $100,000, which is a 127% increase compared to the baseline.

Within the demand disruption context, this situation corresponds to case 4 in section 6.1.2 . Applying the Optimum Disruption Management method, we have the optimal retail price = $660, the new production quantity = 240, and the new supply chain profit = $100,200. By acting upon the demand disruption, the owner eliminates the potential excess inventory and increases the profit by 128% compared to the baseline.

Similar to the demand increase in case 1, the difference in the profit increase between the retail price adjustment and the Optimum Disruption Management method is small (1%) in the analysis above, but it grows larger as the market scale decreases further. For example, the Optimum Disruption Management method will result in $24,200 profit compare to zero profit in the retail price adjustment when the market scale decreases by 50%.

We summarize our results of the effectiveness of demand disruption management in Table 12.

7.2 Numerical Analysis and Discussion on Disruption to the Base Linear Demand in a Decentralized Supply Chain

We use the same linear demand function as in section 7.1 and assume that OEM is the Stackelberg leader. We allocate 50% of the product cost to the CEM, 35% to the OEM, and 15% to the Retailer, or and .

Table 12 Effectiveness of demand disruption management in the centralized supply chain with when the base demand is linear.

Market Scale Change	Demand Disruption		Quantity		Retail Price	Supply Chain Profit	Supply Chain Profit Relative to Baseline
	Case	Method to Manage	Produced	Sold			
+100%	1	None (Baseline)	250	250	$750	$125,000	
+100%	1	Ret. Price Adj.	250	250	$1750	$375,000	+200%
+100%	1	Opt. Disr. Mgmt.	425	425	$1575	$436,250	+249%
+40%	1	None (Baseline)	250	250	$750	$125,000	
+40%	1	Ret. Price Adj.	250	250	$1100	$225,000	+80%
+40%	1	Opt. Disr. Mgmt.	275	275	$1125	$226,250	+81%
+10%	2	None (Baseline)	250	250	$750	$125,000	
+10%	2	Ret. Price Adj.	250	250	$850	$150,000	+20%
+10%	2	Opt. Disr. Mgmt.	250	250	$850	$150,000	+20%
-5%	3	None (Baseline)	250	200	$750	$84,500	
-5%	3	Ret. Price Adj.	250	250	$700	$112,500	+33%
-5%	3	Opt. Disr. Mgmt.	250	250	$700	$112,500	+33%
-10%	4	None (Baseline)	250	150	$750	$44,000	
-10%	4	Ret. Price Adj.	250	250	$650	$100,000	+127%
-10%	4	Opt. Disr. Mgmt.	240	240	$660	$100,200	+128%
-50%	4	None (Baseline)	250	-	$750	-	
-50%	4	Ret. Price Adj.	250	250	$250	$0	
-50%	4	Opt. Disr. Mgmt.	140	140	$360	$24,200	+100%

When there is no disruption, we can calculate using equations (10), (11), and (12) the supply chain total optimum profit $99,456 from selling 136 units with a retail price of $863. The wholesale price from the CEM to the OEM is $137, and from the OEM to the Retailer is $685. The OEM, being the Stackelberg leader, realizes most of the profit (69%) followed by the Retailer (22%) and the CM (9%).

Suppose the market scale is higher than anticipated, . In the baseline case, the demand increase is completely ignored. There are no changes in the production quantity, the retail price, and the profit. However, from equation (4) and (16), we can see that there is an opportunity to increase the retail price to $1264.

In our price adjustment method, we assume there are no changes in the wholesale prices within the supply chain. The profit increase, just like the penalty cost, will be at the Retailer only.

When we apply the Optimum Disruption Management method as in section 6.2, the quantity sold increases to 150 at a $1249 retail price. The new total optimum profit is $160,697, a 62% increase from the baseline and an 8% higher than the price adjustment method above. The OEM still realizes most of the profit, but its share now reduces to 51% while the Retailer's share increases to 42%.

We apply the same logic on the four cases similar to section 7.1 and we tabulate the impact of managing the demand disruption in Table 13.

When the demand increases but ignored, the supply chain profits for each member remain the same as if there is no disruption. However, the Retailer will have to dispose the excess inventory at the end of the second period if no action is taken towards the demand decreases.

Applying the retail price adjustment when the disruption is positive will result in an increase only to the Retailer’s profit because the wholesale price policies remain the same. In this situation, the Retailer chooses not to participate in the Stackelberg game in order to maximize own profit. We see in our numerical example that this method works well when the disruption is positive. However, this method will also penalize only the Retailer when the disruption is negative. The Retailer may still get some profit when the negative disruption is close to the threshold (-10% in our numerical example). As the negative disruption grows larger, the Retailer profit quickly goes away (no profit when the market scale decreases by 50% in our numerical example). The retail price adjustment works best when the disruption is within the threshold for positive disruption and for negative disruption. In fact, the Optimum

Disruption Management method formulated in case 2 and case 3 in section 6.2 is the retail price adjustment method.

The Optimum Disruption Management results in the optimum solution in case 1 and case 4 (demand disruption exceeding the threshold). In case 1, the Retailer gets a bigger portion of the total supply chain profit (increase from 22% to 42%) when the positive disruption is relatively small (40% in our example) and is acted upon. The OEM, being the Stackelberg leader, still retains most of the total supply chain profit (>50%). As the positive disruption gets bigger, the Retailer's profit portion will shrink the as the Retailer will incur more penalty cost due to additional quantity to produce to the original production plan. In our analysis, the Retailer's portion shrinks from 42% to 31% of the total profit when the market scale increases from +40% to +100%. The Retailer's profit portion behaves similarly when the disruption is negative. When the market scale reduces by 50%, the Retailer still gets some profit under the Optimum Disruption Management method compare to none under the retail price adjustment.

Table 13 Effectiveness of demand disruption management in the decentralized supply chain when the base demand is linear.

Market Scale Change	Demand Disruption		Quantity		Wholesale Price to CEM	Wholesale Price to Retailer	Retail Price	Supply Chain Profit				
	Case	Method to Manage	Prod.	Sold				CEM	OEM	Retailer	Total	Rel. to Baseline
100%	1	None (Baseline)	136	136	$137	$685	$863	9%	69%	22%	$99,456	
100%	1	Ret. Price Adj.	136	136	$137	$685	$1,864	4%	29%	67%	$235,008	136%
100%	1	Opt. Disr. Mgmt.	232	232	$233	$1,164	$1,767	8%	60%	31%	$327,349	229%
40%	1	None (Baseline)	136	136	$137	$685	$863	9%	69%	22%	$99,456	
40%	1	Ret. Price Adj.	136	136	$137	$685	$1,264	6%	44%	50%	$153,408	54%
40%	1	Opt. Disr. Mgmt.	150	150	$151	$753	$1,249	7%	51%	42%	$160,697	62%
10%	2	None (Baseline)	136	136	$137	$685	$863	9%	69%	22%	$99,456	
10%	2	Ret. Price Adj.	136	136	$137	$685	$964	8%	61%	31%	$113,055	14%
10%	2	Opt. Disr. Mgmt.	136	136	$137	$685	$964	8%	61%	31%	$113,055	14%
-5%	3	None (Baseline)	136	87	$137	$685	$863	9%	127%	-	N.A.	
-5%	3	Ret. Price Adj.	136	136	$137	$685	$814	10%	74%	16%	$92,655	14%
-5%	3	Opt. Disr. Mgmt.	136	136	$137	$685	$814	10%	74%	16%	$92,655	14%
-10%	4	None (Baseline)	136	37	$137	$685	$863	+	+	-	N.A.	
-10%	4	Ret. Price Adj.	136	136	$137	$685	$764	11%	80%	9%	$85,408	
-10%	4	Opt. Disr. Mgmt.	131	131	$132	$658	$768	10%	76%	14%	$83,432	
-50%	4	None (Baseline)	136	0	$137	$685	$863	+	+	-	N.A.	
-50%	4	Ret. Price Adj.	136	136	$137	$685	$364	+	+	-	N.A.	
-50%	4	Opt. Disr. Mgmt.	76	76	$77	$384	$423	11%	81%	8%	$26,629	

In summary, we can see that the supply chain profit in both the centralized and decentralized models equals the baseline if the demand disruption is positive but ignored. Applying Optimum Disruption Management method will maximize the supply chain profit. When the positive disruption is major, the production plan and the wholesale price policies will be adjusted, and the retail price will be increased. The supply chain will sell the same quantity but at a higher retail price when the demand disruption is positive but minor. In our numerical example, the management of the positive demand disruption in the centralized model results in higher profit increase relative to the decentralized model.

When the demand disruption is negative and ignored, the supply chain will experience higher financial damage in the decentralized model. In our numerical example, the profit decrease in the major negative disruption case is twice the decrease in the minor negative case for both the centralized and decentralized models. In the decentralized model, the Retailer enjoys greater benefit from managing the demand decrease because it carries the burden of financial risk of demand planning.

7.3 Numerical Analysis and Discussion on Disruption to the Base Exponential Demand in a Centralized Supply Chain

Suppose the base exponential demand function is characterized by market scale 1.05×10^{11}, demand elasticity 3, and marginal cost coefficient 1. From Table 5, we calculate the optimal centralized supply chain profit of $125,000, which is obtained by selling 250 units at a retail price of $750.

Let 1 be the demand disruption. The actual demand realized in the second period can be expressed in the new deterministic demand function . The centralized supply chain optimization problem now becomes

where is the new total supply chain profit and .

When actual demand is more than originally planned ( ), equation (37) becomes

The optimum quantity that maximizes the profit can be derived from the first order condition of equation (38):

As can be seen from equation (39), the math becomes much too complicated to find the exact solutions analytically. We will adopt a numerical analysis approach to find the optimum quantity when the base demand is exponential. In the rest of this section and next, we will present the constraints in a similar flavor those of the linear demand function in the previous sections.

The root of the nonlinear equation (39) will give the optimum quantity that maximizes the centralized supply chain profit. However, can be of any value and not necessarily satisfy the constraint . We apply the following property of Limits Function

to investigate.

Suppose the optimum quantity is infinitely close to the originally planned ,

or . Equation (39) becomes:

We apply the similar procedure for the negative disruption and we have

Similar to the threshold parameter in section 6, these will determine whether the disruption is major (case 1 and 4) or minor (case 2 and 3).

Suppose the market scale increases by 400% (5) and the penalty costs for the demand disruption are the same with section 7.1 and 7.2. From equation (40), we know that this disruption belongs to case 1. We use numerical analysis of the Newton Method to find the roots of equation (39). We calculate using the formula:

where 1, 2, 3, 4, …, and from equation (39):

For the initial value , we use the optimum quantity of the base demand 250. After two iterations, we obtain 267 as shown in the table below.

Table 14 Summary of Newton's Method.

1	250	54.99	-3.14	17.51
2	267.51	0.88	-3.04	0.29

We use a similar procedure to calculate the optimum quantity for the different constraint cases. As in section 7.1, we calculate the retail price and the firm's profit for the Optimum Disruption Management method and the retail price adjustment method and tabulated the results in table 15.

In general, we have similar results with the disruption when the base demand is linear in section 7.1. Total profit is higher when the demand disruption is managed, using Optimum Disruption Management method as well as retail price adjustment method. The profit difference between retail price adjustment and Optimum Disruption Management method is not significant when the disruption is small relative to the threshold. However, the Optimum Disruption Management clearly results in higher profit as the demand disruption gets bigger. When the demand decreases by 90% (disruption parameter 0.1), the Retailer will still get profit of $33,649 under Optimum Disruption Management method compared to $24,530 under the price adjustment method.

Table 15 Effectiveness of demand disruption management in the centralized supply chain when the base demand is exponential.

Disruption Parameter	**Demand Disruption**		**Quantity**		**Retail Price**	**Supply Chain Profit**	**Supply Chain Profit Relative to Baseline**
	Case	**Method to Manage**	**Produced**	**Sold**			
10	1	None (Baseline)	250	250	$750	$125,000	
10	1	Ret. Price Adj.	250	250	$1616	$341,457	+173%
10	1	Opt. Disr. Mgmt.	337	337	$1463	$353,272	+183%
5	1	None (Baseline)	250	250	$750	$125,000	
5	1	Ret. Price Adj.	250	250	$1282	$258,120	+106%
5	1	Opt. Disr. Mgmt.	267	267	$1255	$258,606	+107%
2	2	None (Baseline)	250	250	$750	$125,000	
2	2	Ret. Price Adj.	250	250	$945	$173,735	+39%
2	2	Opt. Disr. Mgmt.	250	250	$945	$173,735	+39%
0.8	3	None (Baseline)	250	200	$750	$84,500	
0.8	3	Ret. Price Adj.	250	250	$696	$111,560	+32%
0.8	3	Opt. Disr. Mgmt.	250	250	$696	$111,560	+32%
0.6	4	None (Baseline)	250	150	$750	$44,000	
0.6	4	Ret. Price Adj.	250	250	$633	$95,644	+117%
0.6	4	Opt. Disr. Mgmt.	242	242	$639	$95,708	+118%
0.1	4	None (Baseline)	250	25	$750	–	
0.1	4	Ret. Price Adj.	250	250	$348	$24,530	+100%
0.1	4	Opt. Disr. Mgmt.	163	163	$401	$33,649	+137%

7.4 Numerical Analysis and Discussion on Disruption to the Base Exponential Demand in a Decentralized Supply Chain

Using the same procedure as in section 7.3, we obtain the following threshold parameters when the demand increases

and when the demand decreases

We use numerical analysis of Newton Method from equation (42). When the demand disruption is positive, we have

where 1, 2, 3, 4, …, and

For the decentralized model, we use the same cost allocation as for linear demand. When there is no demand disruption (baseline), profit is maximized by selling 126 units at a retail price of $942. The OEM, being the Stackelberg leader, has the larger share of the profit (51%) followed by the Retailer (41%) and the CEM (8%). We apply the same logic for the different cases of the demand disruption as in the previous sections. The results are tabulated in Table 16.

We find in our example that when the demand is exponential, the initial production plan in the decentralized model is more robust to a demand disruption than the centralized model. From equations (42) and (43), the initial production plan in the decentralized model should not be changed unless the market scale increases more than 406% or decreases more than 37% compared to 310% or 32% in the centralized model.

Similar to the results from the previous sections, the profit is higher when the demand disruption is managed. The supply chain profit is maximized under Optimum Disruption Management method when the disruption is relatively big compared to the threshold. However, we see that the OEM's share of the profit under Optimum Disruption Management method becomes lower than the Retailer's when the disruption is positive. This suggests that the wholesale price contract does not work very well for the Stackelberg leader and another coordination mechanism such as a revenue-sharing contract should be considered.

Table 16 Effectiveness of demand disruption management in the decentralized supply chain when the base demand is exponential.

Market Scale Change	Demand Disruption		Quantity		Wholesale Price to CEM	Wholesale Price to Retailer	Retail Price	Supply Chain Profit				
	Case	Method to Manage	Prod.	Sold				CEM	OEM	Retailer	Total	Rel. to Baseline
11	1	None (Baseline)	126	126	$127	$589	$942	8%	51%	41%	$102,871	
11	1	Ret. Price Adj.	126	126	$127	$589	$2,096	3%	21%	76%	$248,214	141%
11	1	Opt. Disr. Mgmt.	166	166	$166	$925	$1,912	5%	42%	53%	$277,823	170%
6	1	None (Baseline)	126	126	$127	$589	$942	8%	51%	41%	$102,871	
6	1	Ret. Price Adj.	126	126	$127	$589	$1,713	4%	26%	70%	$199,901	94%
6	1	Opt. Disr. Mgmt.	134	134	$134	$778	$1,678	4%	39%	56%	$204,461	99%
2	2	None (Baseline)	126	126	$127	$589	$942	8%	51%	41%	$102,871	
2	2	Ret. Price Adj.	126	126	$127	$589	$1,187	6%	39%	55%	$133,735	30%
2	2	Opt. Disr. Mgmt.	126	126	$127	$589	$1,187	6%	39%	55%	$133,735	30%
0.8	3	None (Baseline)	126	100	$127	$589	$942	9%	56%	36%	$93,949	
0.8	3	Ret. Price Adj.	126	126	$127	$589	$875	9%	56%	36%	$94,359	0%
0.8	3	Opt. Disr. Mgmt.	126	126	$127	$589	$875	9%	56%	36%	$94,359	0%
0.5	4	None (Baseline)	126	63	$127	$589	$942	10%	67%	23%	$79,561	
0.5	4	Ret. Price Adj.	126	126	$137	$589	$748	10%	67%	23%	$78,373	-1%
0.5	4	Opt. Disr. Mgmt.	120	120	$120	$531	$760	9%	58%	33%	$76,473	-4%
0.15	4	None (Baseline)	126	18	$127	$589	$942	+	+	–	N.A.	
0.15	4	Ret. Price Adj.	126	–	$127	$589	$501	+	+	–	N.A.	
0.15	4	Opt. Disr. Mgmt.	92	92	$92	$402	$556	10%	63%	27%	$26,629	

8. CONCLUSION

In this dissertation, we have investigated the impact of the different leadership in a two-period, three-tier decentralized electronics supply chain consisting of a CEM, an OEM and a Retailer. Specifically, we focus on the impact on the profit of the individual supply chain member as well as of the overall supply chain. We began our study with a centralized model where the CEM, OEM, and Retailer are all within one firm. We then extended these results to a decentralized model governed by a wholesale price contract. We apply the Stackelberg solution concept, whose central theme lies in the assumption that the leader, occupying the higher level of hierarchy, can choose his strategy to optimize his operation by taking into account the rational reactions of followers. Three different demand functions are used, i.e. linear, exponential, and stochastic.

In the decentralized model with linear demand, the highest optimum profit will be achieved when the supply chain is led by the Retailer and the unit cost is shared only between the CEM and the Retailer, followed by the supply chain led by the OEM with the unit cost is shared only between the CEM and the OEM. Retailer Stackelberg supply chain is most profitable when 50% or less of the unit cost is absorbed by the CEM, and OEM Stackelberg supply chain is most profitable when more than 50% of the unit cost is absorbed by the CEM. The CEM has the greater share of the profit in the CEM Stackelberg supply chain, followed by the next supply chain member (OEM-Retailer). The OEM has also the greater share of the profit in the OEM Stackelberg supply chain, followed by the next supply chain member (Retailer-CEM). However, this is not the case with Retailer Stackelberg supply chain (Retailer-OEM-CEM).

When the demand is exponential, the highest optimum profit is achieved when a powerful Retailer leads the supply chain and the product unit cost is allocated between the CEM and the Retailer only. Based on our numerical analysis, the CEM Stackelberg will be most profitable when the CEM unit cost is between 20% and 71% of the total product unit cost, and the OEM Stackelberg will have the highest profit when more than 71% of the product unit cost is absorbed by the CEM. The profit distribution of the Retailer Stackelberg and the OEM Stackelberg supply chains are similar to the linear demand case. Unlike in the linear demand case, the Retailer profit in the CEM Stackelberg may be higher than the OEM depending on the product unit cost distribution.

In the stochastic demand function, we model demand randomness as additive disruption in the linear demand function. We show in our numerical analysis that the addition of demand randomness has minimal impact to the optimum overall supply chain profit efficiency under different leadership structures when the demand function is linear. Further study is required to determine if the addition of demand randomness in the two-period model indeed does not impact the overall supply chain profit efficiency.

Using the same supply chain model, we also have investigated the impact of demand disruption when the production plan can no longer be executed as originally formulated. In the first period, the CEM creates a production plan based on the forecast of market demand. The actual demand is realized at the Retailer in the second period.

We began our study with a centralized model where the CEM, OEM, and Retailer are all within one firm. We then extended these results to a decentralized model governed by a wholesale price contract. Our modeling and analysis approaches are applicable to both linear and exponential demand functions.

A penalty cost is incurred when a demand disruption necessitates an increase or decrease in production from the original plan. Additional production requires more expensive resources such as overtime labor, and in this case we show that the supply chain can generate more profit if the demand increase is properly managed. In the case when actual demand is less than the initial plan, the supply chain may have to dispose or sell the leftover inventory to a secondary market, and disruption management can minimize the reduction in supply chain profit. We also show that in some cases it is more profitable for the supply chain to adhere to its original production plan.

When the demand disruption occurs in the decentralized model with linear demand and is managed using the Optimum Disruption Management method, the OEM as the Stackelberg leader retains the larger share of the supply chain profit. However, this is not always true when the demand disruption occurs in the decentralized model with exponential demand. Further study is required to determine if the wholesale price contract indeed does not work in favor of the Stackelberg leader in the case of disruptions with exponential demand.

There are several directions in which our work can be extended. We have assumed that there is only one leader in the supply chain. One extension to our model would be where there are several competing players in each supply chain tiers and multiple leaders. A second direction would be to consider the supply disruption where the Retailer is the Stackelberg leader, which corresponds to situations where major big box retailers gain greater power in the supply chain than the OEMs. A third direction that would be interesting would be to consider an extension to the wholesale price contract, such as a revenue sharing contract, buy-back contract, etc. Finally, it would be interesting to apply robust optimization techniques in the model. Closed-form expressions of key parameters can be derived and will provide a deeper insight into the effect of leadership in the supply chain when the demand function is exponential and stochastic.

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