Mathematical Optimization Approach to Supply Chain Planning and Sourcing Decision with Disruption

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Mathematical Optimization Approach to Supply Chain Planning and Sourcing Decision with Disruption

（災害時を考慮したサプライチェインの計画・調達決定に対する数理最適化アプローチ）

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Dedicated to My Parents

Syed Omor Ali and Ms. Rahima Begum

List of Publications

Chapter 2: Ali, S. M., & Nakade, K. (2014). Scenario-based supply chain disruptions management framework-a quantitative approach. *Innovation and Supply Chain Management*, 8(3), 81–91.

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Chapter 4: Ali, S. M., & Nakade, K. (2015). A mathematical optimization approach to supply chain disruptions management considering disruptions to suppliers and distribution centers. *Operations and Supply Chain Management*, 8(2), 57–66.

Chapter 5: Ali, S.M., & Nakade, K. (2015). Coordinating a supply chain system for production, pricing, and service strategies with disruptions. *International Journal of Advanced Operations Management*. Submitted in June 2015.

Chapter 6: Ali, S. M., & Nakade, K. (2015). Price and service competition of a supply chain system under real-time demand disruptions. *International Symposium on Scheduling*, Kobe, Japan, 99-104.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Introduction

A supply chain system is a network comprised of organizations, people, technology, activities and information in adding values to raw materials and components and transforming them into final products for delivery to end users (Hishamuddin, 2013). A typical supply chain system consists of many partners, who are directly or indirectly connected with one another, forming a complex chain (Figure 1.1). The network performs various activities, which include order processing, supply, manufacturing, inspection and checking, transportation and delivery, and sales and marketing activities, etc. The supply chain activities are regarded as integral parts of any supply chain system (Figure 1.2). In the past, supply chain systems appeared to be small and simple and its activities were usually done smoothly. However, today`s ever evolving supply chain is increasingly complex and geographically spanned across the globe. Therefore, present supply chain systems are prone to various risks and disruptions in such a highly connected world.

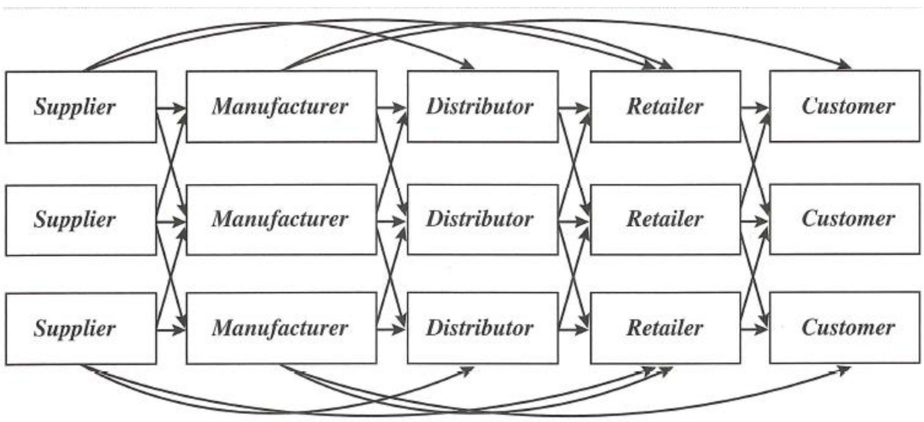

Fig. 1.1 A typical supply chain system (Chopra & Meindl, 2007)

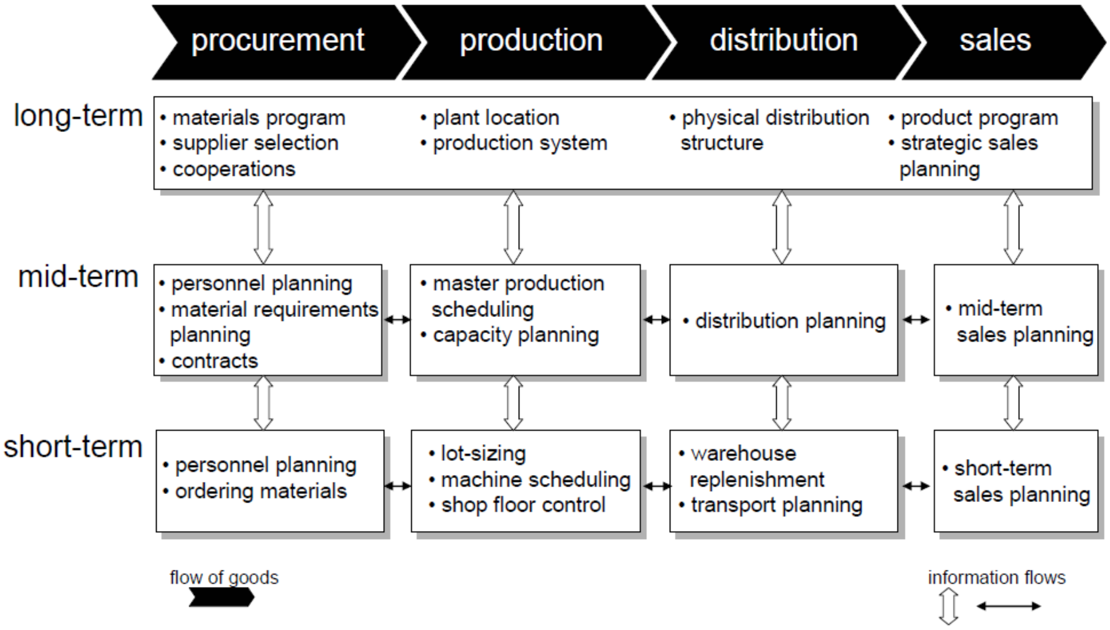

Fig. 1.2 Different activities of a supply chain system (Fleischmann et al., 2005)

In the last two decades, supply chain management has observed some significant key trends such as lean philosophies, sourcing/global sourcing, and shorter product life cycle (Behdani, 2013; Soberanis, 2010). Some of these factors have certainly brought cost efficiency of supply chain systems. However, those trends ultimately make a supply chain system more vulnerable to disruptions. The first and widely applicable trend is the adoption of lean technique in many firms in the world. In a lean management system, one of the major focuses is to reduce inventory, which in turn exacerbates the risk exposure of companies in supply chain system (Aqlan & Lam, 2015; Chopra & Sodhi, 2014). Second, recent supply chain system heavily relies on global sourcing. Although global sourcing offers companies to achieve economic advantage (Johnson et al. 2010), it eventually increases disruptions risk in supply chain networks (Handfield & McCormack, 2008). According to Lynn (2005), many firms in the United States imports largely from China and are at frequent disruptions risk. Noticeably, countries that source from China experience huge supply chain disruptions. The reasons include poor communication, complexity of distribution network, as well as strict tariff and customs rules (Craighead et al., 2007; Soberanis, 2010). Sheffi (2005) indicates that disruptions in supply chain networks bring seemingly unrelated consequences and vulnerabilities as a consequence of global connectivity. Therefore, firms need to robustly analyze their supply chain networks to understand the complex interactions among decision makers (Qiang et al., 2009). With such analysis, planning for disruption would become easier for firms. Third, the life cycle of a product has recently become shorter. Any delays or disruptions in the product development stage could therefore negatively affect not only a firm`s financial performance but also brand reputation.

Quick discovery and response to supply chain disruptions is crucial for minimizing the potential impacts on supply chain networks (Amundson et al., 2014). Firms could thus cope with such ongoing trends. In light of the importance of disruptions management, this research is focused on finding optimal location, production, pricing/service, shipment, and ordering policies with an emphasis on disruptions. To find such strategic decisions, a number of mathematical optimization approaches are proposed throughout this thesis.

The rest of the chapter is structured as follows. Section 1.2 gives the definition and importance of supply chain disruptions management. The rationale of this research is discussed in Section 1.3. The objectives of this research are mentioned in Section 1.4. Finally, Section 1.5 outlines the organization of this thesis.

1.2 Supply Chain Disruptions Management and its Importance

In the `Oxford English Dictionary`, disruption is defined as a disturbance or problems, which interrupt an event, activity, or process. However, the literature of supply chain management gives several definitions of disruptions varying in terms of concepts, meaning and nature. The promising idea of disruptions management is firstly introduced by Clausen et al. (2001) to the supply chain and operational research communities. According to the authors, `` generally, a disrupted situation or just a disruption is a state during the execution of the current operation, where the deviation from plan is sufficiently large that the plan has to be changed substantially``. They successfully apply the idea to solve airline flight and crew scheduling problems in the airlines industry. Yu & Qi (2004) state that disruptions caused by various internal and external factors eventually leading to significant deviation from original plan as well as system performance. Those factors, for example, include machine failures, changes in the price of raw materials as well as delivery time change from vendors, resign of key personnel, technological change, terrorist attacks, epidemic diseases, weather conditions, union strikes, power outages, transportation failures etc.

In the literature, the emerging concept of supply chain disruptions management, in spirit, is mostly related to and originated from supply chain risk management, as illustrated by many researchers. For instance, Tang (2006) divides supply chain risks into operational risk and disruption risk. Similarly, Chopra & Sodhi (2004) view disruptions as a type or source of risk in the supply chain that are unpredictable and rare in nature but catastrophic on the total supply chain system. Furthermore, Tang & Musa (2010) characterize and distinguish disruptions from other risk sources by two features: (1) disruptive events are rare but unforeseen and unpredictable and (2) these events impose considerable negative impacts to the system.

However, some authors deem supply and/or demand uncertainty or supply and demand mismatch as one form of supply chain disruptions. For example, Hendricks & Singhal (2005a, 2005b) mean disruptions as a firm`s inability to match supply and demand. Lin & Wang (2011) associate supply and demand uncertainty to describe supply chain disruptions. Nonetheless, Syndar & Daskin (2006) differentiate supply/demand uncertainty from supply/ demand disruption by stating that disruptions actually make some portion of a supply chain completely inoperative. They further add `` disruptions tend to be infrequent and temporary but cause a significant change to the system when they occur. In contrast, yield uncertainty refers to a form of supply uncertainty in which the quantity produced or received differs from the quantity ordered by a random amount``. Thus, we can say that disruptions actually bring a drastic change in the supply chain network of firms and make the network paralyzed to continue operations.

According to Wagner & Bode (2008), supply chain disruptions are defined as the events that are unintended, undesirable as well as have the capability to degrade both supply chain and business performance to a great extent. Knemeyer et al. (2009) describe disruptions as low probability but high impact events. Craighead et al. (2007) define supply chain disruptions as ``unplanned and unanticipated events that disrupt the normal flow of goods and materials within a supply chain, as a consequence, expose firms within the supply chain to operational and financial risks ``. Organizations therefore require proper planning and response strategies to tackle disruptions regardless of the nature, time, and magnitude of the events triggering the disruptions.

There is some research that connects failure of facilities to discern disruptions from other types of supply chain risks. Snyder & Daskin (2005) consider failure of facilities to introduce disruptions. The authors think that customers would travel from disrupted facilities to non-disrupted facilities in order to have their desired products. Thus, they tackle the impact of disruptions to the supply chain system. Berman et al. (2009) describe disruptions as the periodic failure of service facilities that make them temporarily unavailable for providing service to customers. Moreover, Yang & Yang (2010) perceive disruptions to be the failure at a supplier facility. They stress that such failure ultimately make suppliers incapable of meeting customer demands.

In recent years, we see many examples of supply chain disruptions due to man-made and natural factors. As supply chains are increasingly globalized, the impact of disruptions, irrespective of wherever those take place, seems devastating to many organizations. One of the recent examples taking high level of attentions to the enterprise level is the earthquake and tsunami that struck Japan on March 11, 2011. Apart from causing a tremendous loss of life and property, the disaster also disrupted the global supply chain system. For instance, it is estimated that the Japan disasters caused to decline the production of motor vehicle in North America by 350,000-400,000 units (Canis, 2011). Another shocking disaster in the history of Japan is the Kobe earthquake 1995. The earthquake destroyed all of the transportation links in Kobe. The world’s sixth-largest shipping port in Kobe was also severely damaged due to the impact of the disaster. Further, Toyota decreased its production, due to parts shortages, by 20,000 cars which was equivalent to $200 million worth of revenue (Sheffi, 2005).

In addition, another recent example that affects local and global supply chain as well as the whole nation is the Thailand`s 2011 flood. The disaster disrupted the primary industrial sectors in Thailand, i.e., the automotive and electronics industries and affected the operational capacities of the supply chain. The flood counted economic damages and losses in manufacturing sectors worth of $32 billion which in turn resulted anemic growth of the firms in the region (Haraguchi & Lall, 2014).

In fact, the case of Nokia and Ericsson dramatically exemplifies the concept of supply chain disruptions management to the forefront of public interest. Nokia and Ericsson outsource microchips from Philips. The Philips`s microchips plant in Mexico got shut down due to a fire accident in 2000. The accident caused Ericsson loss for about $ 400 million; while Nokia managed to source from alternative suppliers thus minimized the disruption effect (Latour, 2001; Yu & Qi, 2004). The other notable example is the 2003 U.S.-Canada blackout. It occurred throughout parts of the northeastern United States and eastern Canada on August 14, 2003. This event severely affected the logistics of the companies in the affected area as well as their customers. To continue business, a Chinese publishing company in Beijing quickly rescheduled its production and switched its orders on high-quality paper supplies from a US company in New Jersey to a company in Spain (Yu & Qi, 2004). These examples highlight the importance of introducing supply chain disruptions management tactics, mechanisms, and philosophies to operate and continue the activities of organizations with resilience. After the introduction of disruptions management by Clausen et al. (2001) in the airlines industry in the united states, it is reported that the airlines industry generates savings of tens of millions of dollars (Yu & Qi, 2004).

The above discussions make us realize that modern supply chain systems are highly complex in nature as well as geographically exposed to different regions and countries thus making the supply chain systems highly vulnerable to disruptions caused by man-made and natural reasons. Importantly, these vulnerabilities are fueled by shorter product life cycle, Just-in-Time philosophy, and extreme dependency on outsourcing activities. In a competitive business world, managing the disruption is crucial. In particular, one of the most prominent problems possibly involves planning for and responding to disruptions in sourcing decision. Thus, firms are seeking optimization framework for managing the supply chain disruptions risk in the supply chain that is connected to many partners. The task of optimizing a supply chain system is not an easy task. Moreover, owing to abrupt changes in supply chain systems, optimizing supply chain decisions becomes much more difficult under disruptions. In the context of business continuity management, it's highly demanding to optimize supply chain decision in normal circumstances as well as in disrupted environment. In this research, we try to explore some issues to optimize supply chain with an emphasis on disruptions risk. In the next section, we highlight the rationale of this study.

1.3 Research Rationale

The goal of supply chain risk management is the design and implementation of a supply chain that anticipates and successfully copes with disruptions (Hishamuddin, 2013; Rice & Caniato, 2003). Over the last few years, a growing body of literature has examined the issues of disruptions from the viewpoint of supply chain risk management. We conduct an extensive literature review based on the following points and identify some areas that need attentions. We then address those issues in this research.

1.3.1 Integrating supply and demand disruptions

A considerable stream of studies on disruptions management can be found in the supply chain literature. However, supply/production disruptions seem to receive the most attention (Xia et al. 2004). In the early 1990s, researchers tended to embed supply disruptions into classical inventory models (Snyder & Shen, 2006). Examples include Arreola-Risa & DeCroix (1998), Berk & Arreola-Risa (1994), Gupta (1996), Parlar &

Berkin (1991), and Parlar (1997). In a similar fashion, following an economic production quantity (EPQ) system, Xia et al. (2004) develop a disruption recovery model and suggest a production/inventory plan so as to restore the original (pre-disruption) production plan. They opt to apply disruptions in the form of parameter change and introduce penalty cost for deviation in the original production plan.

In a recent study, Hishamuddin et al. (2010) extend the work of Xia et al. (2004). In contrast to Xia et al. (2004), they incorporate back order and lost sales cost. Paul et al. (2014) further work on Xia et al. (2004) and Hishamuddin et al. (2010) by considering the reliability of production process. Schmitt et al. (2015) examine a multi-location system with supply disruptions. They declare that when demand is deterministic and supply is disrupted, a decentralized inventory system is optimal for the system. Son & Orchard (2013) examine the effectiveness of two inventory policies namely the Q-policy and the R-policy for mitigating the impact of supply disruptions.

Earlier works that introduce demand disruptions in supply chain literature include Qi et al. (2004) and Xu et al. (2003). Qi et al. (2004) investigate the operating plan of a firm in a one-supplier-one-retailer setting in the presence of demand disruption. They consider the linear demand function in their work. In contrast, Xu et al. (2003) use the non-linear demand function and explore the operational issues for the same supply chain system. Over the past few years, there have been many works on demand disruptions. Chen & Zhang (2010) conduct a production control and supplier selection problem with focusing on demand disruptions. Huang et al. (2012) develop a two-period production and pricing decision model to mitigate the effect of demand disruption. Some other works that particularly concentrates on the coordination of supply chain for managing demand disruptions including Cao (2014), Chen & Xiao (2009), and Li et al. (2014) etc.

The above discussion shows that most of the research seems to focus on either supply or demand-side disruptions independently. We believe there is a scarcity of research by linking supply and demand disruptions together for a supply chain network. Moreover, the literature also lacks in studying multi-product supply chain system. This research fills the gap. In order to study supply and demand disruptions, we adopt a supply chain network, which employ a multi-sourcing strategy. Chapter 2 details on this.

1.3.2 Conditional Value at Risk (CVaR) approach to supply chain disruptions management

Conditional Value at Risk (CVaR), defined as the mean of the tail distribution exceeding VaR, has become one of the popular risk measures in finance industry as well as other areas (Zhu & Fukushima, 2009). In fact, since the introduction of more tractable auxiliary function in the form of convex or linear program by Rockafellar & Uryasev (2000, 2002) to minimize CVaR, many researchers have shown considerable interest to apply the CVaR approach for risk management in practice. The application of CVaR is observed in various fields such as portfolio management (Zhu & Fukushima, 2009), inventory management (Qiu et al., 2014), power planning (López et al., 2015), and supply chain risk management (Wu et al., 2010; Xu et al., 2013).

Xu et al. (2013) examine the concept of Conditional Value at Risk (CVaR) in a supply contract model. They conclude that the risk attitude of the manufacturer plays an important role in supply chain decesion making. There are a number of studies that apply the CVaR criterion in the newsvendor context. Lim et al. (2015) construct a risk-averse inventory cost model using CVaR. Their model could determine the optimal inventory level that seems to be useful for risk-averse decision makers. Wu et al. (2014) inspect a newsvendor problem with order quantity and price competition under the CVaR measure. The authors discover that the supplier`s performance is greatly influenced with respect to the risk attitude of the newsvendors.

Problems connected with CVaR approach in supply chain disruptions management can be found, among others, in Sawik (2011a, 2011b, 2013). In a recent literature, Rabbani et al. (2014) propose a multi-objective model for supplier selection problem. They consider CVaR measure to deal with delays, disruptions, and quality risk issues.

All these work are carried out by focusing on supply disruptions.

Research on the application of CVaR in disruptions management for a supply chain network by considering supply and demand disruptions together is limited. This topic is elaborately discussed in Chapter 3.

1.3.3 Integrating production and storage facilities disruptions

Production/supply disruptions and the disruptions/failure of storage facilities have been very common in supply chain networks due to increasing man-made and natural disasters. Xia et al. (2004) note that production/supply disruptions have been attracted to many researchers. In addition to the aforementioned papers on production/supply disruptions in Section 1.3.1, some other examples include Chen et al. (2012), Hou & Zhao (2012), Nejad & Kuzgunkaya (2014), Qi (2013), and Snyder (2014). Most of the supply disruptions studies are based on a single/dual sourcing problem (Qiang et al., 2009). It is also observed that multi-product supply chain studies are also rare in supply chain risk management. This research is attempted to grasp supply chain structures with multi-sourcing strategy in which each supplier is capable to produce and supply multiple products in the distribution systems.

There are two methods to tackle disruptions risk to distribution systems (Medal et al. 2014). First, the systems need to strategically locate facilities. Another method is to harden/protect facilities. Facility hardening means to build a facility such that it gets additional safety standards to sustain disasters. A growing number of studies exist on the facility location problems with disruptions. The pioneering work includes Drezner (1987) in which random facility failures are considered in the p-median problem. This work is extended by others (Berman et al., 2007; Lee, 2000; Snyder & Daskin, 2005). Current related works, for example, contain Garcia-Herreros et al. (2013), Jabbarzadeh et al. (2012), Li et al. (2013). Most of these works aim to locate suitable facilities to hedge against disruptions. However, Medal et al. (2014) integrate facility location and facility hardening decision to reduce the risk of disruptions.

To-date, disruptions to suppliers or storage facilities (e.g., distribution centers) have been treated separately in most of the academic literature. In this research, these two aspects are modeled together. It may be an interesting research agenda to strategically locate distribution centers by including the assumption that disruptions tend to happen to both the suppliers and the distribution centers. We explore this research scheme in Chapter 4.

1.3.4 Price and service competitions under demand disruptions

Pricing and service strategies appear to be the two important managerial decisions in the successful operations of firms. Towards this end, some authors have been motivated to consider both price and non-price factors in supply chain and marketing literature. Initially, Iyer (1998) and Tsay & Agrawal (2000) inspect non-price coordination mechanisms. The non-price factors, for example, include the provision of product information, free repair, faster-checkout, or after-sales service etc. Xiao & Yang (2008) investigate the price and service competition of supply chains with risk-averse retailers. They observe that the optimal supply chain strategies are greatly influenced by the retailers` risk sensitivity. Lu et al. (2011) examine manufacturers` competition under manufacturer service and retail price. This model is further enhanced in Zhao et al. (2013) by considering fuzziness of the consumer demand, manufacturing cost, and service cost. Wu (2012) builds a model on price and service competition between new and remanufactured products. They test the model in a two-echelon supply chain and identify equilibrium price and service strategies for all the supply chain members.

The motivation to examine the price and service strategies of supply chains with disruptions could be explained from two aspects.

Firstly, a survey of the literature manifests that less attention has been paid to model price and service competition under disruptions. Thus, it would probably be an interesting research theme to find the responsive pricing and service strategies for mitigating the impact of disruptions. It is worth noting that most of the works on service competition assume that the manufacturer in a supply chain system is competing on service. This assumption would be relaxed in this research. It is thought that the retailers in the system compete on price as well as service. Therefore, the retailers would be more enthusiastic to provide better service for attracting consumers.

Secondly, real-life experience shows that consumers tend to go to the retail outlets that deal with customers softly and provide them with the required service they ask for. Therefore, retailers` service carries immense significance in competitive markets. Importantly, retailers` commitment has links to sustainable development (Lavorata, 2014).

It is believed that the service of retailers is increasingly significant in normal supply chain as well as in disrupted supply chain. Thus, this research has been undertaken to investigate price and service competition model subject to disruptions. Chapter 5 discusses this issue.

1.3.5 Supply chain strategies with disruptions under a coordination framework

In a coordinated supply chain system, the members of the supply chain may behave as a part of a unified system thus improving the overall performance of the supply chain (Arshinder et al., 2011). Numerous research works have been appeared in the area of supply chain coordination (Aydin et al., 2015; He & Zhao, 2012; Hu et al., 2013). Recently, supply chain coordination models to deal with disruptions are rapidly emerging. Wang & Zhang (2007) test a one-supplier-one-retailer supply chain system with demand disruptions. They apply an all-unit wholesale quantity discount (AQD) policy and a capacitated linear pricing (CLP) policy to tackle the demand disruptions. Zhang et al. (2012) investigate the coordination policies of a one-supplier-two-retailers supply chain with demand disruptions. They find that revenue sharing contract is useful to coordinate the supply chain. Zhang et al. (2015) provide the coordination mechanism of a dual channel supply chain with demand/production cost disruptions. They establish the coordination by utilizing a wholesale price contract, a direct channel`s price, and a lump sum fee. They expose that the supply chain strategies are heavily dependent on the level of disruptions. Cao et al. (2015) investigate the coordination of a supply chain system composed of one supplier and multiple competing retailers under simultaneous demand and production cost disruptions. They use revenue sharing contract to achieve the coordination.

This research is carried out to consider disruptions at two factors, namely demand and service sensitivity coefficient. With the philosophy of coordination in mind, the benefits and applicability of revenue share contracts to derive optimal supply chain decisions in terms of production, pricing, and service for a one-supplier-one-retailer supply chain system are illustrated. Readers are relegated to Chapter 6 for the details.

1.4 Objectives of the Research

The key aim of this thesis is to study and formulate optimization framework to plan for and respond to disruptions in souring decision. To fulfill this aim, the specific objectives are as follows:

(i) To develop a mathematical model for a multi-product-multi-agent supply chain system subject to supply and demand disruptions.

(ii) To construct a Conditional Value at Risk (CVaR) model for a multi-product -multi-agent supply chain system subject to supply and demand disruptions.

(iii) To formulate a mathematical model for selecting the location of distribution centers (DCs), and to establish the shipment policies of a multi-echelon supply chain system subject to supply and facilities disruptions.

(iv) To coordinate a one-supplier-one-retailer supply chain system subject to demand and service sensitivity factor disruptions. In order to achieve this objective, revenue sharing contract mechanism is applied here.

(v) To study the price and service competition of a supply chain system consisted of one supplier and multiple competing retailers facing demand disruptions. Optimal price and service strategies are investigated.

The story-line of this thesis is summarized in Figure 1.3. The cases considered here and the relationship among them is briefly shown in Figure 1.4.

1.5 Organization of the Thesis

The thesis is comprised of seven chapters. The contents of each chapter are briefly discussed below:

The current chapter discusses some background and the rationale of the research, and also outlines the objectives of this study.

Chapter 2 presents a linear programming (LP) model to deal with supply and demand disruptions of a multi-product supply chain system comprised of multiple suppliers and multiple distributors. This model also ensures the quality and delivery performance requirement of end customers. We vary the intensity of supply and demand disruptions to examine the model. The model gives ordering policies to a given set of suppliers in a pre-disruptions and post-disruptions supply chain environment.

Chapter 3 is an extension of the previous model given in Chapter 2. In this Chapter, we illustrate a Conditional Value at Risk (CVaR) model that focuses on minimizing the expected worst-case cost of the supply chain system. While the model in Chapter 2 minimizes the expected cost of the supply chain system, the CVaR approach in Chapter 3 is intended to model extreme cost scenarios of the system. The CVaR model is numerically examined by applying several confidence levels, and supply and demand scenarios. The model gives ordering policies to plan for possible disruptions.

Chapter 4 is devoted to presenting a mixed integer programming (MIP) model in which we minimize the sum of investment cost for renting facilities and the expected transportation cost from suppliers to distribution centers, as well as from distribution centers to end customers. This model deals with disruptions to suppliers and distributor centers and produce outputs in terms of location decisions and shipment decisions.

Chapter 5 provides a supply chain coordination model to deal with real-time demand disruptions of a one-supplier one-retailer supply chain system. We begin with applying the Manufacturing Stackelberg (MS) game and then investigate the production, price, and service strategies under a coordinated scheme namely revenue sharing contract with an aim to improve the efficiency of the supply chain. The model presented therein is an unconstrained non-linear optimization problem and yields output in terms of production/ordering decisions, and pricing and service decisions to respond to disruptions.

Chapter 6 introduces the price and service competition of a supply chain system under real-time demand disruptions. The supply chain system consists of one manufacturer and multiple retailers competing on price and service. We inspect the supply chain under both centralized and decentralized settings. For analyzing the competition under the decentralized supply chain setting, the Manufacturing Stackelberg (MS) game between the supplier and the retailers is employed. On the contrary, the differentiation technique is simply used to study the competition in the centralized supply chain. Like the coordination model presented in Chapter 5, the competition model stated in Chapter 6 is also an unconstrained non-linear optimization formulation.

Finally, Chapter 7 gives conclusions and applications of this research. In addition, a number of avenues for the future research are also indicated in Chapter 7.

We provide Appendices at the end of the thesis. Those contain some equations related to Chapter 6.

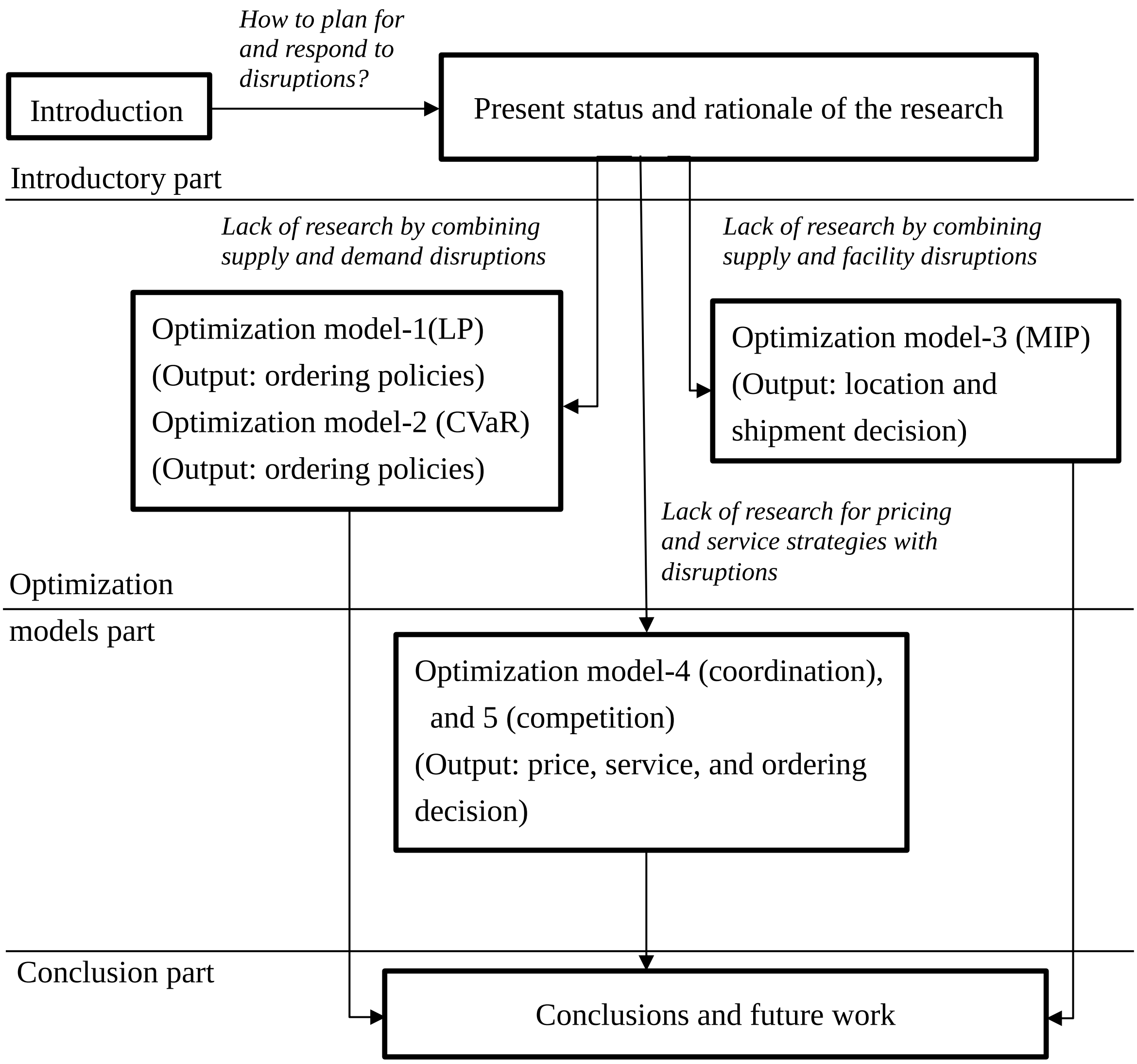

Fig. 1.3 The story-line of this thesis

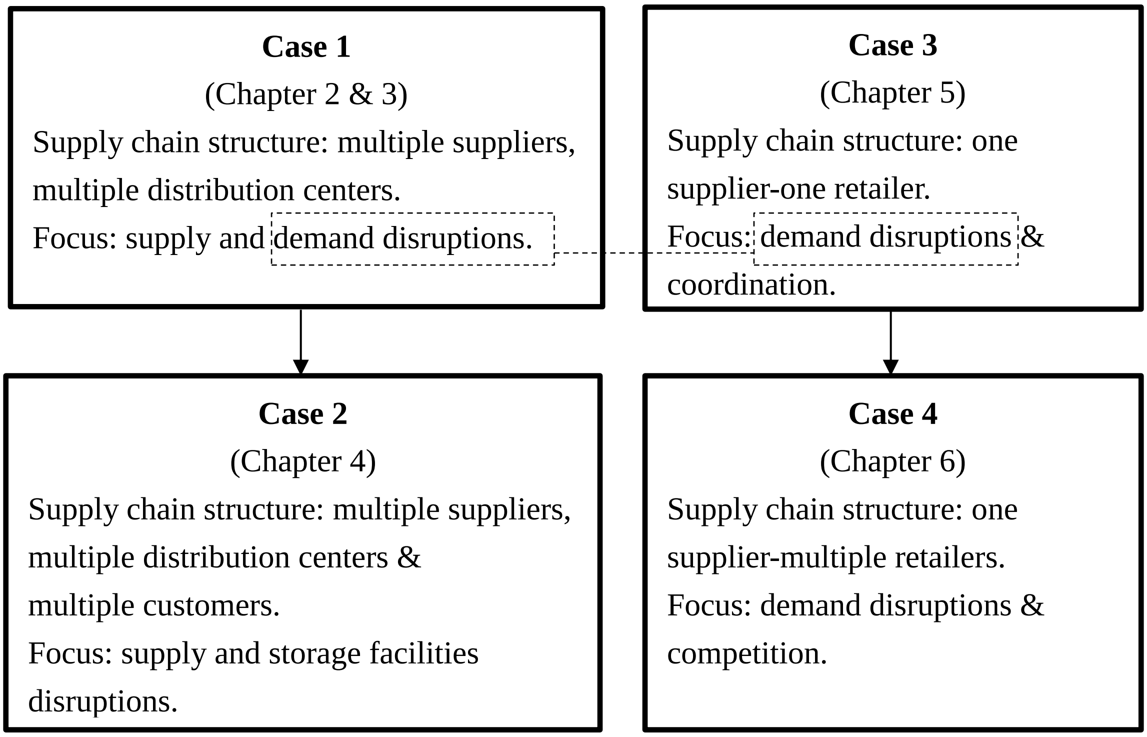

Fig. 1.4 The cases studied in this thesis

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Chapter 2

Scenario-Based Supply Chain Disruptions Management Framework: A Risk-Neutral Optimization Approach

2.1 Introduction

In the age of globalized economy, the supply chains of a company are long, complex, and geographically diverse across the globe. Therefore, the supply chains are getting more and more vulnerable to disruptions caused by natural disasters or man-made actions. The world has experienced several natural and man-made disasters in the last few decades. A list of examples includes earthquakes, tsunami, political instability, supplier bankruptcy, economic crises, SARS, strikes, terrorist attacks etc. The aftermath of such events shows that the severity and complexity of supply chain disruptions are increasing at an alarming rate and thus imposing threat on market share and enterprise existence. Hendricks and Singhal (2005) report that supply chain disruptions have long term negative effects on the supply chain financial performance. For example, some companies suffer 33-40% lower stock returns than expected as a result of disruptions. Usually, a supply chain system is intended to perform well under disruption-free environment. However, disruptions are almost inevitable in today's complex supply chains, which are characterized by the prevalent time sensitive turbulent business environment. The best business plans are those that could anticipate and prepare for this inevitability, in particular, to deal with global sourcing (Handfield & Mccormack, 2008). In fact, supply chain disruption is attracting growing attention after some high profile disasters in the world over some years. Thus, a growing stream of research is recently seen to explore the recovery and mitigation strategies of supply chain disruptions (Agrawal & Pak, 2001; Blos et al., 2015; Craighead et al., 2007; Falasca et al., 2008; Handfield & Mccormack, 2008; Hendricks and Singhal, 2005; Kim et al., 2014; Lodree Jr & Taskin, 2008; MacKenzie et al., 2014; Murino et al., 2011; Papadakis, 2006; Sodhi & Tang, 2009; Schätter et al., 2015; Wu & Blackhurst, 2007; Xia et al., 2011).

In the literature, the promising concept of supply chain disruption has been originated as a branch of supply chain risk management. For instance, Tang (2006) divides supply chain risks into two categories: operational risk and disruption risk. In addition, Chopra & Sodhi (2004) classify supply chain risks into nine parts: disruptions, delays, systems, forecasts, intellectual property, procurement, receivables, inventory, and capacity. Furthermore, disruptions can also be classified on the basis of the changes in parameter or links in a system. For example, firms may experience production disruptions (Chen & Lin, 2008), supply disruptions (Bimpikis et al., 2015), demand disruptions (Chen & Zhang, 2010), price disruptions (Cavallo et al., 2014), schedule disruptions (Hishamuddin et al., 2010), transportation disruptions (Liu et al. 2015) etc.

In this chapter, we integrate the upstream and the downstream supply chain disruptions of a supply chain network. In particular, we consider supply and demand disruptions. When the supplier is disrupted, he fails to supply a pre-ordered amount to the customer. Further, disruptions tend to change the properties of the demand of a product. Therefore, the decision maker in the supply chain tends to modify his sourcing plans. In our proposed research, an attempt has been made to integrate the supply and the demand disruptions by considering a scenario-based approach. The approach captures a pre- and post-disruption tradeoff to tackle the issues of disruptions.

Recently, a number of researchers start to model supply disruptions or demand disruptions by adopting quantitative approach. In fact, recent high profile catastrophic events such as Nepal earthquake 2015, Japan tsunami 2011, the hurricane Katrina and Rita in 2005, the Indian Ocean earthquake and tsunami in 2004, terrorist attack 9/11, etc. have motivated many researchers to include supply chain disruptions risk into procurement and supply chain (Chopra & Sodhi, 2004; Dillon & Mazzola, 2010; Kleindorfer & Saad, 2005; Knemeyer et al., 2009; Mackenzie et al., 2012; Meena et al., 2011; Oke & Gopalakrishnan, 2009; Tang, 2006; Yu et al., 2009). Other types of catastrophic events that can interrupt business operations are snowstorms, heavy rain, excessive wind, fire, industrial and road accidents, strikes, and changes in government regulations (Ellis et al., 2010; Stecke & Kumar, 2009). Thus, the possibility of supply disruptions should be considered during decision making. Some authors suggest dual and/or multiple sourcing as one of the efficient strategies to mitigate supply chain disruption risk (Allon & Van Mieghem, 2010; Argod & Gupta, 2006; Chiang & Benton, 1994; Cooke, 2011; Davarzani et al., 2011; Gupta et al., 2015; Huang & Xu, 2015; Kelle & Miller, 2001; Minner, 2003; Parlar & Perry, 2010; Prasanna & Kumanan, 2011; Silbermayr & Minner, 2014; Tomlin, 2006; Wang & Gilland, 2009; Xiaoqiang & Huijiang, 2009; Yang et al., 2012, Yu et al., 2009). It is believed that multiple sourcing is more reliable to hedge against disruptions; however, it adds additional cost for negotiation, making contract and monitoring the quality (Moritz & Pibernik, 2008).

A well-known example that highlights supply disruption and the effectiveness of dual sourcing strategy is the case of Nokia-Ericsson in 2000.The Philip`s microchips plant was shut down due to a fire accident. It caused Ericsson loss for about $400 million, while Nokia managed to source from alternative suppliers thus minimized the disruption effect (Latour, 2001). Another notable example includes the Japan earthquake and tsunami in 2011. This disaster severely disrupted the global supply chain. For instance, the supply of flash memory from Japan was reduced after the disaster. Notably, Japan is the world`s leading supplier of dynamic random access memory and flash memory. Flash memory is used in standard logic controllers (SLC), liquid crystal display (LCD), and LCD parts and materials. After the disaster, the prices of the components soared by 20% (Park et al., 2013). Moreover, Automakers-such as Ford, Chrysler, Volkswagen, BMW, Toyota, and GM-depend on Japanese supply chain, had to temporarily shut down some operation after the earthquake and tsunami (Canis, 2011; Ye & Abe, 2012).

These large scale disruptions carry devastating negative impacts on firms` performance in domestic and international level. Thus, decision makers are now rethinking on finding strategies for firms in the presence of disruptions risk. Right after the Japan disaster, companies that heavily relied on single sourcing were trying to find new sources to avoid running out of components that had been obtained from Japan (Fisher, 2011; Fujimoto & Park, 2014; Hookway & Poon, 2011). This example shows the importance of having multiple suppliers to cope with supply disruptions.

Tang (2006) points out that demand disruptions carry significant impact on the planning and activities of supply chain. In 2008, many firms around the globe experienced large scale demand disruptions due to the global financial crisis. For instance, nearly 1000 toy manufacturers were shut down in Southern China in 2008 because of the sudden order cancellation from the United States and Europe. Chen & Zhang (2010) examine the effects of demand disruptions on production control and supplier selection problem. They consider a three-echelon supply chain system and model the customer demand as a jump-diffusion process. There is some literature (for example, Cao, 2014; Li et al., 2014) that applies the coordination mechanism to manage demand disruptions.

Most of the papers cited above consider either supply or demand disruptions separately. However, this work treats supply and demand disruptions together. A scenario based approach is used to integrate the effect of supply and demand disruptions. The proposed work provides a way to explore a tradeoff analysis with respect to optimal ordering politics in pre- and post-disruption situation and the relevant costs. Note that it is also a challenging task to maintain the quality and the in-time delivery of products for a supply chain under disruptions risk. We therefore include the quality aspects of products and the delivery performance of suppliers in the proposed model. Thus, the model would yield response policies in the event of disruptions while confirming the quality and delivery performance requirements of the decision makers in the supply chain.

The rest of the chapter is structured as follows. Section 2.2 discusses the problem statement. Section 2.3 addresses the analytical framework. Section 2.4 deals with related computational experiments. Finally, Section 2.5 concludes the chapter.

2.2 Problem Statement

This chapter studies a supply chain consisting of multiple agents-outside suppliers $\mathrm{I} = \{1,2, \dots, \mathrm{I}\}$, local supplier, and distributors (DBs) $\mathrm{L} = \{1,2, \dots, \mathrm{L}\}$ as shown in Figure 2.1.

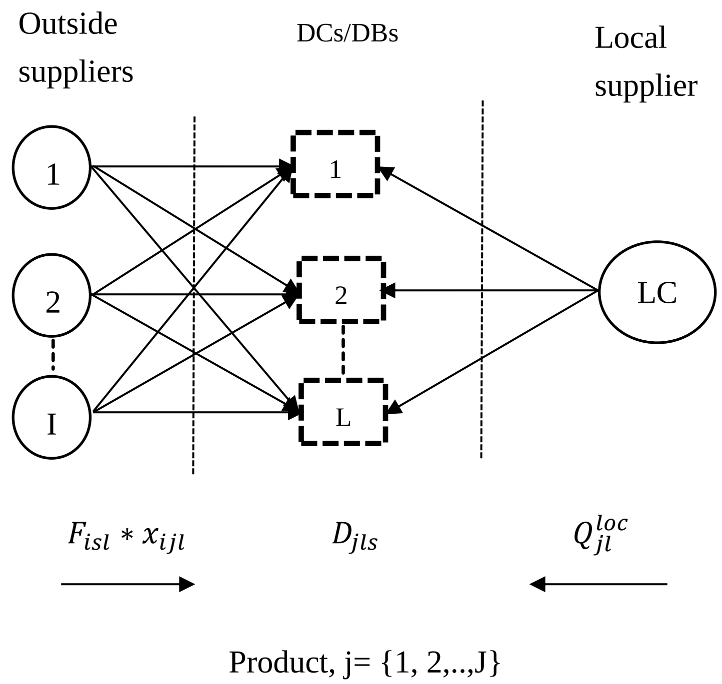

Fig. 2.1 Schematic diagram of a multi-product multi-agent supply chain

Each product j in a set of products is outsourced from a local supplier of amount $Q_{jl,}^{loc}$ as well as from outside suppliers i ∈ I of amount x_{ijl} to distribution centers l ∈ L. There are many factors that shape consumer demand. Such factors, for example, include the price and type of products, income of the consumer, geographical location etc. Further, from our experience we see that the demand of products also varies with the information/occurrence of disruptions. For instance, some consumers want to buy more petroleum oil when they hear about Middle East instability. Like demand disruptions in the products` market of interest, suppliers also experience disruptions. As a result, the suppliers are not able to smoothly run their production process. In order to effectively face supply disruptions, dual or multiple sourcing is an option, which is more or less discussed in the supply chain risk management literature. The proposed supply chain system has a fixed and reliable local supplier having limited capacity. It is assumed that the local supplier has no disruption effect. Therefore, the local supplier acts as a backup supplier to mitigate disruption effect at the expense of additional cost though. Each distributor purchases the products from two or more outside suppliers thus adopting multiple sourcing (Figure 2.1). The outside suppliers are subject to disruptions. The orders are allocated to the local and the outside suppliers in such a way that the effect of disruptions and the relevant cost are minimized. Thus, a tradeoff in ordering policies and the related costs in pre- and post-disruption situation exist in the system.

While disruptions happen in the supply side, supply properties change. The properties of demand also change when a firm experiences demand disruptions in the market. Any form of interruptions or deviations from regular supply or demand amount might be thought of as disruptions in a supply chain system. To capture the changes in supply and demand, we utilize the fraction of order $F_{isl,}$ and the product demand D_{jls} with a focus on the effect of disruptions on the parameters. Several scenarios are generated for the parameters. Each scenario $s \in S$ specifies the related demand and order percentage values that are taken from the respective normal distribution characterized by the intensity of disruptions. The amount of planned inventory is affected as a result of supply and demand disruptions. Eventually, the response (ordering emergency quantities) to the local supplier varies accordingly.

It is worth mentioning that one of the most important considerations in any outsourcing decision is the quality of the incoming products as well as receiving the ordered products in time. Because, company reputation and brand image greatly depend on quality and delivery performance. Considering these aspects, several authors (Akarte & Surendra, 2001; Cameron & Shipley, 1985; Dickson, 1996; Li & Zabinsky, 2009) describe the importance of employing quality and delivery performance requirements when firms are involved in outsourcing. In this chapter, a mathematical optimization approach is proposed for a multi-product multi-agent supply chain for the planning of disruptions. The developed framework takes into account the purchasing cost, inventory holding costs, and emergency ordering cost. In addition, two constraints namely the quality and delivery performance are added in the framework. Note that we follow a risk neutral decision making in this study. In risk neutral decision, the decision maker considers a set of policies that minimizes the expected cost of the supply chain system.

In the proposed model, the decision variables related to ordering portfolio are the initial order to the local and the outside suppliers, and the emergency order to the local supplier. The emergency order is based on the amount of inventory after disruptions. When disruptions happen, the capacities of the outside suppliers are reduced thus some fraction of the initial order could be supplied by the outside suppliers, while the local supplier is able to supply the amount as ordered. Based on this observation, the decision maker estimates the level of inventory and then he finds the amount of shortages to fulfill the demand thereby stimulating for emergency order at a higher cost. This work minimizes the sum of cost to purchase products from the local supplier, and the expected total cost, which is comprised of the expected purchasing, inventory, and emergency ordering cost. We consider single period model and the items are consumed linearly over time. Therefore, we assume average inventory cost for simplicity.

2.3 Model Formulation

The index sets, decision variables, and parameters used in this study are as follows:

Sets	***Descriptions***
I	*Set of outside suppliers*
J	*Set of items*
L	*Set of distribution center*
S	*Set of scenarios*

Variables	***Descriptions***
x_{ijl}	Amount of item j ordered from supplier i at distribution center l, $i \in I, j \in J,$ and $l \in L$
Q_{jl}^{loc}	Amount of item j ordered from local supplier at distribution center l, $j \in J,$ and $l \in L$
Q_{jls}^{eme}	Emergency order placed for item j at distribution center l under scenario s. $j \in J, l \in L,$ and $s \in S$
I_{jls}	Inventory level of product type j in distribution center l under scenario s, $j \in J, l \in L,$ and $s \in S$

Parameters	***Descriptions***
P_s	Probability of scenario s, $s \in S$
D_{jls}	Demand of item j in distribution center l in disruption scenario s, $j \in J, l \in L,$ and $s \in S$
H_{jl}	Unit inventory cost of product type j in distribution center l, $j \in J,$ and $l \in L$
INV_{jl}^{max}	Inventory limit at a distribution center for a product type in a scenario s, $j \in J, l \in L,$ and $s \in S$
c_{ijl}	Unit cost (in \$/unit) of item j quoted by supplier i to distribution center l, $i \in I, j \in J,$ and $l \in L$
C_{jl}^{loc}	Unit cost (in \$/unit) of item j quoted by fixed local supplier to distribution center l in normal condition, $j \in J,$ and $l \in L$
C_{jl}^{eme}	Emergency cost per unit (in \$/unit) to be added to unit cost quoted by local supplier in normal condition, $j \in J,$ and $l \in L$
ρ_{jl}	Lost sales cost per unit (in \$/unit) of product j from distribution center l, $j \in J,$ and $l \in L$
Q_{jl}^{minloc}	Minimum order to local supplier for a product type j at a distribution center, l in normal condition $j \in J,$ and $l \in L$
Q_{jls}^{maxloc}	Maximum order to local supplier for a product type j at a distribution center l under scenario, s $j \in J, l \in L,$ and $s \in S$
F_{isl}	Percentage of order supplied by the outside supplier i in scenario s to distribution center l, $i \in I, s \in S,$ and $l \in L$
q_{ij}	Fraction of poor quality items of type j from supplier I, $i \in I, j \in J$
q_j^{loc}	Fraction of poor quality items of type j from local supplier, $j \in J$
t_{ij}	Fraction of late items of type j from supplier i, $i \in I, j \in J$
τ_j	Pre-set quality tolerance factor for product type j, $j \in J$
τ_d	Pre-set delivery tolerance factor expressed as percentage of demand

In the next, the constraints of the proposed model are given in Section 2.3.1; the analytical framework is presented in Section 2.3.2.

2.3.1 Constraints in the proposed model

The model considers six types of constraints. Those are inventory constraints, emergency order constraints, quality and delivery performance constraints, capacity constraint, and finally the non-negativity constraints. These constraints are illustrated below:

Inventory constraints:

The inventory of product i at distribution center l in a scenario s is equal to the product received from the local supplier plus incoming flows from outside suppliers. Notice that due to the impacts of disruptions on the outside suppliers, they could not supply the whole amount, x_{ijl} as is previously ordered before disruptions took place. Hence, the effect of disruptions is taken by the factor $F_{isl,}$ which varies depending on the type and extent of disruptions. Moreover, it may also vary depending on the location and distance of the distribution centers from the outside suppliers. Because, the mode of transportation and the goods carried within those modes are also affected by disruptions. Thus, the following equation holds:

$$I_{jls} = Q_{jl}^{loc} + \sum_{i \in I} F_{isl}\, x_{ijl,} \quad \forall j \in J, l \in L, s \in S.$$

The inventories are limited by their corresponding upper bound. This upper bound is based on the distribution centers` capacities to store a particular type of product.

$$I_{jls} \leq INV_{jls,}^{max} \qquad \forall j \in J, l \in L, s \in S.$$

Emergency order constraints:

An emergency order needs to place if there is a shortage of inventory to meet the demand and is determined by the following equation:

$$Q_{jls}^{eme} \geq D_{jls} - I_{jls,} \quad \forall j \in J, l \in L, s \in S.$$

As illustrated earlier, emergency order is placed to the local supplier who works as a backup source to mitigate the effect of disruptions imposed by outside suppliers.

Quality and delivery performance constraints:

The following constraints fulfil the requirements for high quality and on-time delivery of the received items from the suppliers. Since, the requirements for high quality and on-time delivery of the received items are generally expressed as a percentage of demand in the real world business practices (Li & Zabinsky, 2009); we can express the required quality performance as

$$\sum_{i\in I} q_{ij} \sum_{s\in S} F_{isl}\, x_{ijl} + q_j^{loc} Q_{jl}^{loc} + q_j^{loc} \sum_{s\in S} Q_{jls}^{eme} \leq \tau_j \sum_{s\in S} D_{jls,} \quad \forall j \in J, l \in L.$$

Here, τ_j is the quality tolerance factor for specific product type received at the distribution center and expressed as a percentage of demand.

Furthermore, the delivery performance can be expressed as

$$\sum_{i\in I} t_{ij} \sum_{s\in S} F_{isl}\, x_{ijl} \leq \tau_d \sum_{s\in S} D_{jls,} \quad \forall j \in J, l \in L.$$

Here, τ_d is the pre-set delivery tolerance factor expressed as a percentage of demand.

Supplier capacity constraints:

We assume that outside suppliers have infinite capacity. On the contrary, the ordering quantities to the local supplier in normal and emergency situation are restricted by the following constraints respectively.

$$Q_{jl}^{loc} \geq Q_{jl,}^{minloc} \qquad \forall j \in J, l \in L.$$

$$Q_{jls}^{eme} \leq Q_{jls,}^{maxloc} \qquad \forall j \in J, l \in L, s \in S.$$

The local supplier is employed here as a backup source to manage disruptions. However, the quantity that can be sourced a priori is dictated by the local supplier.

Non-negativity constraints:

The non-negativity and integrality conditions associated with the decision variables are as follows:

$x_{ijl}, Q_{jl}^{loc}, Q_{jls}^{eme}, I_{jls} \geq 0, \quad \forall i \in I,\ j \in J,\ l \in L,\ s \in S.$

2.3.2 Proposed model

The model presented here is based on some assumptions given below:

i. The local supplier is not subject to disruptions whereas outside suppliers are prone to disruptions. Therefore, the outside suppliers can`t supply a pre-scheduled amount.
ii. Purchasing cost from outside suppliers is lower than the purchasing cost from the local supplier.
iii. The local supplier`s capacity is limited.
iv. All outside suppliers have infinite capacity.
v. The model assumes a single period.

By utilizing the aforementioned variables, parameter, and the constraints, the analytical framework is formulated as

$$Min\ Z = \sum_{j\in J}\sum_{l\in L} Q_{jl}^{loc} C_{jl}^{loc} + \sum_{s\in S} P_s \Big\{ \sum_{i\in I}\sum_{j\in J}\sum_{l\in L} F_{isl}\, x_{ijl} c_{ijl} + \sum_{j\in J}\sum_{l\in L} \tfrac{1}{2} H_{jl} I_{jls} + \sum_{j\in J}\sum_{l\in L} \big(C_{jl}^{eme} + C_{jl}^{loc}\big) Q_{jls}^{eme} \Big\}. \tag{2.1}$$

Subject to,

$$I_{jls} = Q_{jl}^{loc} + \sum_{i\in I} F_{isl}\, x_{ijl}, \quad \forall j \in J, l \in L, s \in S, \tag{2.2}$$

$$Q_{jls}^{eme} \geq D_{jls} - I_{jls}, \quad \forall j \in J, l \in L, s \in S, \tag{2.3}$$

$$\sum_{i\in I} q_{ij} \sum_{s\in S} F_{isl}\, x_{ijl} + q_j^{loc} Q_{jl}^{loc} + q_j^{loc} \sum_{s\in S} Q_{jls}^{eme} \leq \tau_j \sum_{s\in S} D_{jls}, \quad \forall j \in J, l \in L, \tag{2.4}$$

$$\sum_{i\in I} t_{ij} \sum_{s\in S} F_{isl}\, x_{ijl} \leq \tau_d \sum_{s\in S} D_{jls,} \quad \forall j \in J, l \in L, \tag{2.5}$$

$$I_{jls} \leq INV_{jls,}^{max} \qquad \forall j \in J, l \in L, s \in S, \tag{2.6}$$

$$Q_{jls}^{eme} \leq Q_{jls,}^{maxloc} \quad \forall j \in J, l \in L, s \in S, \tag{2.7}$$

$$Q_{jl}^{loc} \geq Q_{jl,}^{minloc} \qquad \forall j \in J, l \in L, \tag{2.8}$$

$$x_{ijl}, Q_{jl}^{loc}, Q_{jls}^{eme}, I_{jls} \geq 0, \quad \forall i \in I, j \in J, l \in L, s \in S. \tag{2.9}$$

The objective function is given by Equation (2.1). The objective function is composed of four terms. The first term is the sum of cost incurred to procure the products from the local supplier. The second term indicates the expected purchasing cost for buying the products from the outside suppliers. The third term computes the average inventory holding cost. The fourth term evaluates the expected emergency purchasing cost. Equation (2.2) determines the inventory level of each product at each distribution center in a scenario s. Equation (2.3) establishes the emergency order. Equations (2.4) and (2.5) impose quality and delivery performance requirements. Firm`s inventory limit for each item at each distribution center is enforced through Equation (2.6). Equations (2.7) and (2.8) limit the ordering quantity to the local supplier. Finally, Equation (2.9) is the non-negativity constraints associated with the decision variables. Details of these constraints are given in Section 2.3.1.

2.4 Computational Experiment

In this section, numerical experiments are performed to demonstrate the effectiveness and applicability of the proposed model in practice. Let us consider a simple supply chain consisting of two outside suppliers, one local supplier, and two distribution centers. It is mentioned that all suppliers have the capacity to produce all categories of product of interest. There is a central purchasing manager who analyzes the demand and inventory state at each distribution center. We investigate a simple multi-product case where the purchasing manager decides to outsource two categories of product from the three suppliers. We execute several test instances in order to examine the performance of the model. At first, we consider a number of demand and order fraction scenarios and run the model. The optimum objective function values (OFB) and CPU time are recorded to see the behavior of the model. We commence the experiment with 15 scenarios and continue up to 1,000 scenarios, with each having the same probability of occurrence. Note that a decision maker may assign different probabilities based on disruptions database and experience. Otherwise, a generic approach to assigning the same probabilities to each of the scenarios could be used for analysis purpose. Here, we consider normal probability distribution for the product demand and order fraction realization. Other parameters such as costs and quality/delivery tolerance factors are also assumed in this study.

Table 2.1 summarizes the range of data of the test problems. We use this range for each test instance. The number of scenarios used for each test instance is shown in Table 2.2. In Table 2.1, the range of data is shown only for clarity. We use some fixed values for the tolerance factors in this study. A purchasing manager, however, can use different values of the quality and tolerance factor based on his judgement. Of course, the model would then produce different results. Notice that we don't mention any particular product for which the range of data presented in Table 2.1 could match with. Rather, we leave the question of revalidated the model by applying data from real field. The model could be applied to any product categories by suitable adjustment of the range of data.

Table 2.1 Range of data for the test problems

Parameters	Range of data
Product Demand	D~N(3500, 500)
Fraction of order/ outside	F~N(0.80, 0.10)
Purchasing cost/outside ($)	[7,9]
Purchasing cost/local ($)	[10,13]
Inventory cost ($)	[1,2]
Emergency cost ($)	[12,14]
Quality tolerance factor	[0.02,0.04]
Delivery tolerance factor	[0.02,0.04]
Ordering limit/local	[600,50000]
Inventory Limit	[20,000]

Table 2.2 Optimum objective function value (OOFV) and CPU times for 10 test cases

Test instance	# of scenarios	Optimum objective function value (OOFV)	CPU time (seconds)
T-1	15	140,686.564	1.935
T-2	30	140,797.792	3.135
T-3	50	141,162.282	5.195
T-4	100	144,484.660	10.545
T-5	200	144,217.401	20.577
T-6	300	144,490.606	30.873
T-7	400	143,922.565	41.138
T-8	500	143,226.570	57.018
T-9	700	143,715.236	74.803
T-10	1000	143,180.592	101.120

To make the model more realistic, data related to the product demand and the fraction of order supplied by the outside suppliers for any products type could be achieved from the historical information of supply and demand disruptions. We can directly utilize those benchmark values to test the model. In the absence of real data, many parameters can be generally modelled as normal distribution. In fact, many real world events could be described by normal distribution as it holds the variation that really persists in a natural environment. As such, normally assumption is widely invoked in the literature (Petkov & Maranas, 1989; Tacq, 2010). Thus, we model the demand and the percentage of order as normally distributed random variable with mean and standard deviation. In this analysis, we assume, product demand is normally distributed with mean value 3500 and standard deviation value 500 i.e. $D \sim N\,(3500, 500)$. Similarly, the percentage of order supplied by the suppliers is assumed to be normally distributed with mean 0.80, standard deviation 0.10 i.e. $F \sim N\,(0.80, 0.10)$. For the test instances, T-1 to T-10, we generate samples for each of this parameter with the help of GAMS (24.1.3)-CPLEX platform with CPLEX 12.5.1.0 version. In the next, the demand and order fraction values are used to validate the model. We consider many scenarios for analysis purpose thus seeking to examine the behavior of the model in terms of computational efficiency, optimum objective function value (OOFV), and the values of the decision variables. The mathematical model presented in this chapter is coded on GAMS 24.1.3 and run by CPLEX 12.5.1.0 solver on an Intel (R) Core (TM) i7-3770 Dual Processor with 24GB RAM and a 3.40GHz CPU.

We solve the mathematical model by applying linear programming (LP) technique. In a linear programming problem, we find the maximum or minimum value of a linear expression that is called the objective function. The largest or smallest value of the objective function is called the optimum objective function value (OOFV). If the problem is to maximize profit, then we get the largest value of the objective function. On the contrary, for a cost minimization problem we get the smallest value of the objective function. In this study, we minimize the expected cost of the supply chain system. Therefore, the solution gives the minimum (optimum) cost value of the objective function. The values of the decision variables that give the optimum value of the objective function constitute an optimal solution. Generally, a risk neutral decision maker aims to minimize expected cost. The optimum objective function values (OOFV) and CPU time of the model for the test instances are given in Table 2.2.

A modeler may be interested to explore the behavior of the model for higher number of scenarios. Figure 2.2 shows the optimum objective function values (OOFV), solution runtime with regard to the test instances considered in this numerical investigation. Each test instance indicates a number of scenarios as represented in Table 2.2. According to Figure 2.2, the objective function values increases up to test instance-4, which consists of 100 scenarios. Then, the objective function values tend to decrease with the increase of number of scenarios. This might be due to the fact that after certain point, the average cost decreases with the higher number of scenarios, which is an intuitive observation. On the other hand, the graph shows an exponential increase of CPU time with the increase of number of scenarios. We experience no computational burden up to this stage of numerical investigation. The importance and challenge of computational optimization is found in Fidanova (2013), Yang et al. (2013).

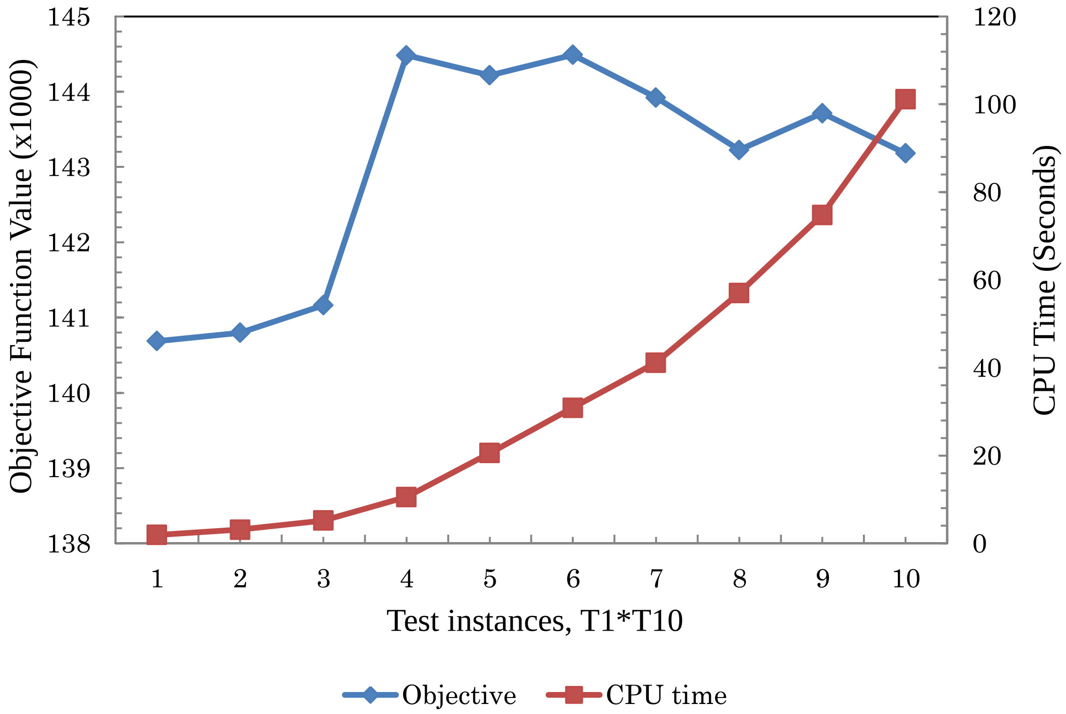

Fig. 2.2 Optimum Objective function value (OOFV) and CPU time for 10 test cases

The runtime statistics of the model in terms of number of iterations required for converging to optimum solution, number of variables, and number of equations are shown in Table 2.3. From Table 2.3, we see that we have 8,013 variables and 16,013 equations for the test case T-10 that has 1000 number of scenarios. Thus, for this test case, the model converges to optimality after 8349 iterations. For higher number of scenarios, the number of variables and equations are higher. As a result, higher computation time is reported for those test instances. From the numerical experiments, it is concluded that GAMS-CPLEX can solve the large scale model having significant number of scenarios, variables, and equations with reasonable computation time. A modeler (decision maker) would like to solve the model quickly for decision making. Therefore, computational ease is one of the most important requirements to managers in real life. In particular, if the management decision relies on analytical frameworks for resolving numerous issues, there is no denying the fact of solvability of the model within short time. For more complex models, heuristics or new algorithm is needed.

Table 2.3 Runtime statistics of the model for the test cases

Test instance	# of scenarios	# of iterations	# of variables	#of equations
T-1	15	128	133	253
T-2	30	255	253	493
T-3	50	419	413	813
T-4	100	827	813	1613
T-5	200	1658	1613	3213
T-6	300	2474	2413	4813
T-7	400	3283	3213	6413
T-8	500	4127	4013	8013
T-9	700	5891	5613	11213
T-10	1000	8349	8013	16013

2.4.1 Effect of demand variance and order fraction variance on expected total cost

There are many parameters used in the model. For instance, product demand, fraction of order supplied from outside suppliers, inventory holding cost, purchasing cost, emergency ordering cost etc. we discuss some of those in this chapter. A sensitivity analysis is carried out to show the effect of parameter changes on the objective function value (OFV)/expected total cost. A noteworthy pattern may be observed to conclude a meaningful insight on disruptions management. When it comes to disruptions planning, the analyses related to the effect of demand variance or the fraction of order variance might uphold significant insights to firms. In this regard, firms may build suitable strategies to guard their supply chain against disruptions. Therefore, this section is aimed at examining the effects of demand variance and fraction of order variance on the expected total cost. In order to fulfill this aim, first of all, we want to see the effect of demand variance on the objective function while keeping the fraction of order variance fixed. For conducting the sensitivity analysis, we pick the intermediate test instance T-5 having 200 scenarios. We choose test case T-5 as an example and for the sake of simplicity. Of course, any test set could be selected for the sensitivity analysis.

We consider ten sets of experiment to analyze demand variance on the objective function values (OFV). The standard deviation values used in the range of 100 to 550 i.e., σ^d_{min}=100, σ^d_{max} = 550. We begin the test with standard deviation 100, and increase the standard deviation value by 50 in every successive trial, and continue the test up to standard deviation 550. The mean demand is fixed at 3500 units for all the trials. The change of total cost with respect to the variation of demand is shown in Figure 2.3. It can be seen that the total cost for the system increases with an increase in demand variance while other parameters are kept fixed. In addition, we see an approximately linear increase of the total cost with an increase of the demand variance thus reflecting an expected observation.

In the next, we examine the effect of fraction of order variance on the expected total cost. We use the same test instance (T-5) for this purpose. The demand properties are fixed at D (3500,500), which is actually attributed to the problem modeled initially. To this end, we select σ^f_{min}=0.02, σ^f_{max}= 0.12 as the minimum and maximum standard deviation respectively for the fraction of order. The other values of standard deviation are 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09 and 0.10 for this analysis. The behavior of the total cost with respect to order fraction variance is illustrated in Figure 2.4.

It is noted that the mean order fraction is kept constant for all the trials. The mean fraction of order equals 0.80 here. This value is originally used for the initial sets of numerical experiment. Figure 2.4 shows an increasing effect on the expected total cost with an increase of order fraction variance while the other parameters are fixed. As depicted in Figure 2.4, the expected total cost remains more or less fixed up to third observation. Then, it shows a somewhat linear growth up to standard deviation 0.12. Thus, in can be concluded that for the higher variation in supply amount, the cost incurred in the system would be considerably higher. In other words, more supply disruption is obviously impacting on the diminishing of profits of the supply chain`s partners. As we consider supply and demand disruptions in this study, the sensitivity analysis is limited to the variability of supply and demand. However, the analysis could be performed on other parameters as well.

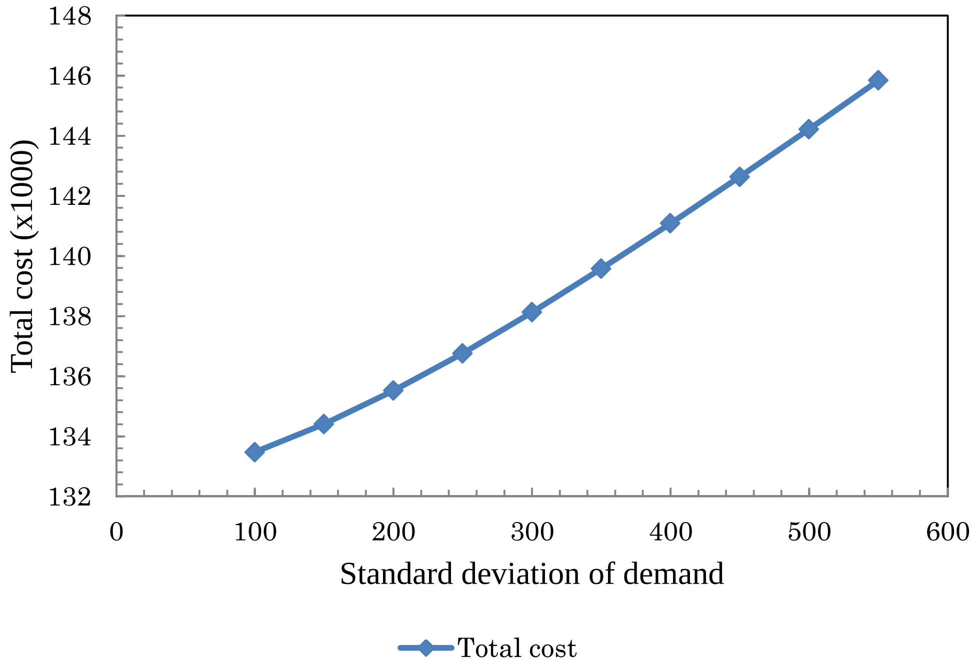

Fig. 2.3 The change of total cost with respect to demand variability

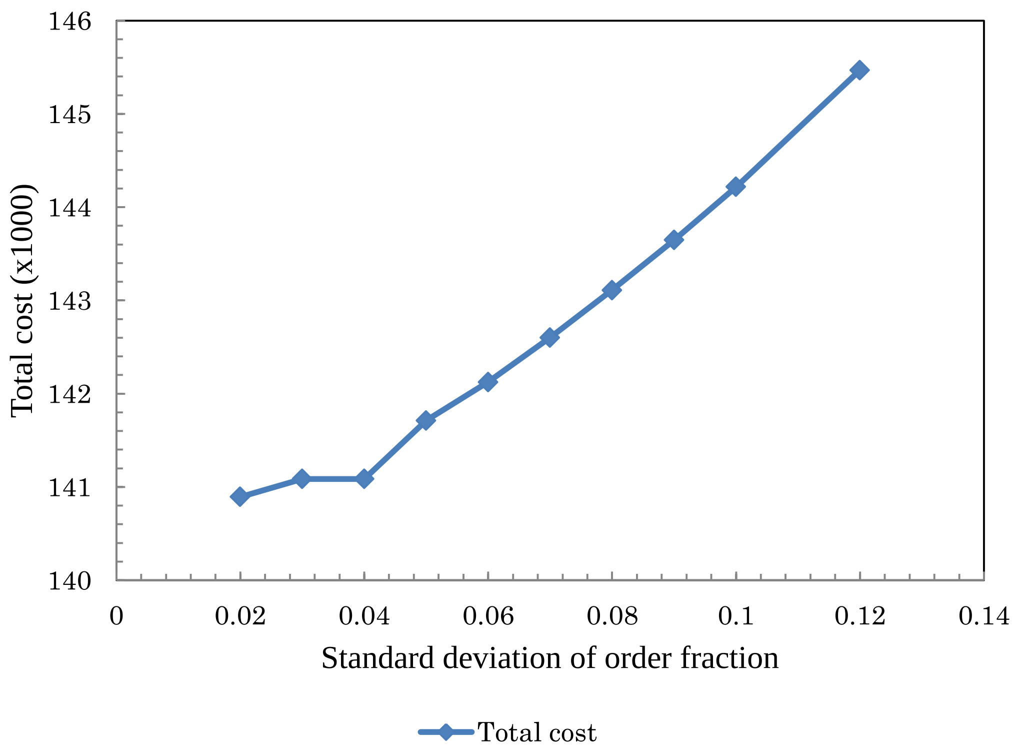

Fig. 2.4 Effect of increasing fraction of order variance on total cost

2.4.2 Effect of mode of disruptions on sourcing decision

We have conducted computational experiment so far by treating the disruptions in a generic form and consider the homogenous properties of demand and order fraction. However, the properties of demand and order fraction would be obviously characterized by the intensity of disruptions in reality. We classify the modes of disruptions into four types: high impact, moderate impact, low impact, and very little impact. Hence, to analyze such insights, in this section, the demand and order fraction scenarios are defined on the basis of the mode of disruption impact. In particular, this section intends to assign different expectation of random parameters based on the vulnerabilities of disruptions. Thus, we consider 1000 scenarios and categorize them on the basis of the mode of disruption impact. These scenarios are composed of high (10%), moderate (30%), low (40%), and very little impact (20%) scenarios. That means that a subset of scenarios represent high impact, moderate impact, low impact, and very little impact amounting 100, 300, 400, and 200 respectively.

The properties or expectation of the demand of products vary in a diversified fashion in practice and therefore it’s not a straightforward anticipation. Sometimes, the fluctuation of demand due to disruptions might differ according to the category of product. For example, when disaster strikes a place, the demand for first aid product is increased whereas the demand for luxury product is decreased in that area. However, it’s rather simple to assume the expectation related to order fraction. It is due to the fact that when disruptions intensity would be higher, the amount of product received by the decision maker would be low in comparing to low impact disruptions. To be realistic, one needs to gather real data from firms on the pattern of product demand as well as order fraction in the state of disruptions. Herein, for the analysis purpose, let us consider different demand and order fraction properties corresponding to mode of disruption impact. We assume that the mean values of demand and order fraction change with the mode of disruptions impacts. Table 2.4 and Table 2.5 summarize the properties of demand and order fraction that are characterized by disruptions intensity. Although, this analysis is performed for 1000 scenarios, for the sake of clarity we mention a few results of the decision variables in Table 2.6, Table 2.7, and Table 2.8 respectively. From Table 2.6, it is seen that the ordering quantities are the same irrespective of the properties of the demand and order fraction used in the model. This might be due to the fact that the minimum ordering quantities to the local supplier are to be placed before disruptions and these variables are independent of scenarios. Thus the results illustrate minimum ordering quantities which are intuitive observations.

Table 2.4 Demand properties characterized by disruptions intensity

Mode of disruptions impact	Demand (D)
High impact	D~N(3000, 500)
Moderate impact	D~N(3350, 500)
Low impact	D~N(3500, 500)
Very little impact	D~N(3700, 500)

Table 2.5 Order fraction properties characterized by disruptions intensity

Mode of disruptions impact	Order fraction (OF)
High impact	F~N(0.60, 0.10)
Moderate impact	F~N(0.70, 0.10)
Low impact	F~N(0.80, 0.10)
Very little impact	F~N(0.90, 0.10)

Table 2.6 Order quantities to local supplier in homogenous and heterogeneous properties of demand and order fraction

Decision variables (Q_{jl}^{loc})	Solution obtained (D/OF homogeneous)	Solution obtained (D/OF heterogeneous)
J1L1	600	600
J1L2	600	600
J2L1	600	600
J2L2	600	600

Table 2.7 Order quantities to outside suppliers in homogenous and heterogeneous properties of demand and order fraction

Decision variables (x_{ijl})	Solution obtained (D/OF homogeneous)	Solution obtained (D/OF heterogeneous)
I1J1L1	2207.482	1790.877
I1J1L2	3936.134	3997.203
I1J2L1	1677.489	2063.741
I1J2L2	1778.912	2044.206
I2J1L1	1738.857	2167.253
I2J1L2	0	0
I2J1L1	2146.846	1845.388
I2J2L2	2103.544	1967.848

Table 2.7 shows the ordering portfolio to the selected set of outside suppliers for the homogenous and heterogeneous properties of demand and order fraction. It is observed that the ordering quantities are distributed and diversified to different suppliers. We don't observe any stable pattern/trend for the ordering portfolio to the outside suppliers. In some cases, higher quantities are ordered when we use the homogeneous expectation of demand and order fraction whereas in some cases different results are reported. It is hard to draw any specific conclusions from the results as appeared in Table 2.7. In general, the ordering quantities are based on the supply and demand scenarios, as well as other cost factors. Table 2.8 shows the emergency ordering quantities to the outside suppliers for the homogenous and heterogeneous properties of demand and order fraction. As observed, no stable pattern/trend is observed for emergency ordering quantities for the homogeneous and heterogeneous properties of demand and order fraction. However, in contrast to the results in homogenous supply and demand

properties (J1L1S14- J1L1S20), emergency orders need to place for the heterogeneous properties in some cases. We think that the solutions are possibly based on the heterogeneous supply and demand realization scenarios. The computational experience and the sensitivity analysis with respect to the demand and order fraction make us draw a conclusion that the solutions of the model are highly dependent on supply and demand disruptions scenarios while other cost and tolerance factors are maintained at a fixed level.

Table 2.8 Emergency order quantities in homogenous and heterogeneous properties of demand and order fraction

Decision variables (Q_{jls}^{eme})	Solution obtained (D/OF homogeneous)	Solution obtained (D/OF heterogeneous)
J1L1S1	143.396	332.997
J1L1S2	0	28.433
J1L1S3	414.800	153.566
J1L1S4	0	0
J1L1S5	152.162	371.468
J1L1S6	234.078	720.416
J1L1S7	0	0
J1L1S8	0	0
J1L1S9	97.751	56.798
J1L1S10	0	237.876
J1L1S11	241.008	470.481
J1L1S12	355.653	0
J1L1S13	725.467	243.534
J1L1S14	0	159.753
J1L1S15	0	280.774
J1L1S16	0	701.001
J1L1S17	0	0
J1L1S18	0	367.188
J1L1S19	0	0
J1L1S20	0	0

2.5 Conclusions

In this chapter, a quantitative framework is presented with a view to planning for disruptions in upstream and downstream supply chain. To sum up, some key features of the model include the determination of ordering portfolio, ensuring the quality performance of the receiving products as well as meeting the delivery performance of the outside suppliers. We also study the effect of demand variance and fraction of order variance on expected total cost. The results show more or less linearly increasing effect on the expected total cost in both cases. Further, in this analysis, we also include the mode of disruptions impact defined by disruptions intensity. The analysis highlights that the demand and order fraction scenarios carry significant impact on the values of the decision variables. To the best of our knowledge, no other works consider the mode of disruptions previously.

Note that we minimize the expected cost of the proposed supply chain structure. Thus, we optimize supply portfolio under supply and demand disruption within a risk-neutral decision making perspective. One interesting research direction may be to examine the model by considering risk-averse decision making perspective. Chapter 3 deals with this aspect. Readers are referred to Chapter 3, in which we build a Conditional Value at Risk (CVaR) model to minimize the extreme cost of the supply chain.

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Chapter 3

Scenario-Based Supply Chain Disruptions Management Framework-A CVaR Approach

3.1 Introduction

Today`s ever evolving supply chains are long, complex, and geographically spanned across the globe. Therefore, disruptions on one part of a supply chain tend to affect the other parts through global supply chain network. Thus, supply chain systems become more vulnerable to disruptions caused by natural disasters or man-made actions (Ali & Nakade, 2014). With increasing awareness to business continuity management, organizations are looking for appropriate response/recovery mechanisms to adjust to disruptions in a short span of time. It is needless to say that disruptions, with their unanticipated nature, carry huge impact on resources, profit, and company reputation. Therefore, planning for disruptions is absolutely vital to organization`s success. According to Hendricks and Singhal (2005), supply chain disruptions carry long term negative effects on the supply chain financial performance. For example, some companies suffer 33-40% lower stock returns relative to their benchmark as a result of disruption. Thus, it is noticed that disruptions, by its nature, can make a supply chain system paralyzed with its economic, operational, and reputational harms. Traditional supply chain systems are usually designed for operation under a smooth and normal environment. Those perform well if everything goes right. However, in the real world, disruptions do occur in a rapidly transforming and turbulent business environment. The best business plans are those that can anticipate and prepare for this risks and inevitability (Handfield & McCormack, 2007; Lee et al., 2010). Thus, researchers in the area of supply chain risk management, in present times, show immense interest to explore response/recovery mechanisms to handle disruptions (Ali & Nakade, 2014; Ali & Nakade, 2015; Hisamuddin et al., 2014; Macdonald & Corsi, 2013; Paul et al., 2014; Paul et al. 2015; Whitney et al., 2014).

In the literature, some researchers inspect and categorize supply chain disruptions as a branch of supply chain risk management. For instance, Tang (2006) divides supply chain risks into operational risk and disruption risk. Moreover, Chopra and Sodhi (2004) classify supply chain risks into disruptions, delays, systems, forecasts, intellectual property, procurement, receivables, inventory, and capacity. Disruptions cause the deviation of parameters` properties in a system (Finke et al., 2012). Based on this attribute, several types of disruptions are in place. Some examples include production disruptions (Chen & Lin, 2008), supply disruptions (Ali & Nakade, 2015), demand disruptions (Qi et al., 2004), price disruptions (Cavallo et al., 2014), schedule disruptions (Hishamuddin et al., 2010), etc. For the purpose of mitigating the negative impact of disruptions on supply chain, it is imperative to formulate proactive/reactive planning strategies by considering local and global factors to disruptions. Therefore, there is an increasing trend to include disruptions management in decision framework of firms over the last decade. In this chapter, we integrate supply and demand disruptions and formulate a Conditional Value at Risk (CVaR) model for a multiple-suppliers multiple-products supply chain system.

Over the years, some researchers concentrate on building quantitative frameworks to deal with supply chain disruptions. Actually, recent high profile catastrophic events such as Japan tsunami 2011, the hurricane Katrina and Rita in 2005, the tsunami in 2004, terrorist attack 9/11, etc. have drastically raised the issues of disruptions management to the forefront of researchers and practitioners. Thus, a growing number of works include supply chain disruptions risk into procurement and supply chain (Chopra & Sodhi, 2004; Dillon & Mazzola, 2010; Kleindorfer & Saad, 2009; Knemeyer et al., 2009; MacKenzie et al., 2012; Meena et al., 2011; Oke & Gopalakrishnan, 2009; Tang, 2006; Yu et al., 2009). Other types of catastrophic events responsible for business interruptions are snowstorms, heavy rain, excessive wind, fire, industrial and road accidents, strikes, and changes in government regulations (Ellis et al., 2010; Stecke & Kumar, 2009). In the literature of supply chain disruptions management, most of researchers are concerned with managing supply side risk. To this point, some authors suggest dual and/or multiple sourcing as one of the efficient strategies to mitigate supply chain disruption risk (Allon

& Van Mieghem, 2010; Argod & Gupta, 2006; Chiang & Benton, 1994; Cooke, 2011; Davarzani et al., 2011; Kelle & Miller, 2001; Minner, 2003; Parlar & Perry, 1996; PrasannaVenkatesan & Kumanan, 2011; Tomlin, 2006; Wang et al., 2009; Xiaoqiang & Huijiang, 2009; Yang et al., 2012; Yu et al., 2009).

A notable example of supply chain disruptions is the case of Nokia-Ericsson in 2000. The Philip`s microchips plant in Mexico suffered a fire accident. It caused Ericsson loss for about $400 million, while Nokia managed to source from alternative suppliers and thus minimized the disruption effect (Latour, 2001). One recent large scale disaster that disrupts local and global supply chain network is the Japan earthquake and tsunami in 2011. Japan is the world`s leading supplier of dynamic random access memory and flash memory. After the catastrophic disaster, the prices of the components are soared by 20%, showing the impact of the disaster on global supply chain (Park et al., 2013). Further, many automakers such as Ford, Chrysler, Volkswagen, BMW, Toyota, and GM, that depend heavily on Japanese supply chain, made their operations stopped after the earthquake and tsunami due to parts shortage (Canis, 2011).

Demand disruptions also carry significant impact on supply chain (Tang, 2006). In 2008, the world suffered a global financial crisis. Chen and Zhang (2010) mention that nearly 1000 toy manufacturers were shut down in Southern China in 2008 because of the sudden order cancellation from U.S and Europe. They examine the effects of demand disruptions on production control and supplier selection problem for a three-echelon supply chain system. Many researchers focus on implementing coordination mechanisms to tackle demand disruptions. Qi et al. (2004) are the first to introduce coordination schemes to manage demand disruptions for a supply chain comprised of one supplier and one retailer. Dong and Ming (2006) extend their work considering demand and price factor disruptions. Moreover, Xiao et al. (2007) investigate the coordination mechanism for a supply chain with one manufacturer and two competing retailers with demand disruptions. They establish the coordination of the supply chain by applying a linear quantity discount policy or an all-unit quantity discount policy. The effect of bearing the production deviation costs by the manufacturer or the retailers is also investigated in their work.

The above discussion highlights some research in the area of supply chain disruptions management. The literature provides some promising models for disruptions management. It also shows the importance of disruptions management to sustain business and organization. Therefore, the significance of disruptions planning can`t be overlooked in the present social, economic, and geographical context of supply chains.

Despite a number of studies in the area of supply chain disruptions management, few of them apply any structured risk management measures. In the literature of financial engineering and management, two risk management measures are widely used. Those are Value at Risk (VaR) and Conditional Value at Risk (CVaR) (Sarykalin et al., 2008). VaR and CVaR are extensively applied for optimal portfolio selection in financial management. Uryasev (2000), and Rockafellar and Uryasev (2000) present a new approach to selecting a portfolio with the reduced risk of high losses. Their approach optimizes a portfolio by calculating VaR and minimizing CVaR simultaneously. Apart from financial risk management, recently, the approach attracts many researchers from other areas as well. For example, Gotoh & Takano (2007) apply CVaR concept in the context of classic newsvendor problem and minimize the expected cost. Chen et al. (2009) examine how the newsvendor under CVaR criterion makes pricing and replenishment decisions. Chahar and Taaffe (2009) use Conditional Value at Risk (CVaR) approaches to control the number of profitable but risky demands to consider in the procurement policy. Catalão et al. (2012) formulate a risk managemen model to limit profit volatility by applying CVaR concept. Furthermore, Sawik (2011) applies Value at Risk (VaR) and Conditional Value at Risk (CVaR) concepts to control the risk of supply disruptions. The author formulates a single/bi-objective mixed integer program which could select supplier and supply portfolio while ensuring minimization of disruptions risk. Some authors (Ma et al., 2010; Xu et al., 2009) build a type of supply chain coordinations framwork under CVaR measures.

We notice that few papers consider CVaR approach in the supply chain literature to quantitatively model supply chain risk. To our knowledge, in the domain of supply chain disruptions researches, the application of CVaR is not rich enough till today. The above mentioned papers on CVaR don’t focus on response policies for a multi-product multi-agent supply chain system subject to disruptions risk. Thus, we apply CVaR approach to form a quantitative disruption management framework for a multi-product multi-agent supply chain with an emphasis on supply and demand disruptions. The framework determines response policies in terms of ordering portfolio to the available set of suppliers in a pre-disruptions and post-disruptions circumstances. Importantly, the proposed CVaR model would minimize the worst case cost of the system of our interest.

For better understanding of the contents of this chapter, a definition of different terms used here is given below:

Disruptions: any forms of unplanned and unexpected events that hinder regular supply chain operations. For instance, a list of such events includes labor strike, machine breakdown, industrial accident, political instability, currency fluctuation, economic breakdown, earthquake, cyclone, tornado, etc.

Scenarios: When disruptions happen to suppliers, their capacity to produce/supply a pre-scheduled amount is reduced. Similarly, disruptions tend to change the properties of market demand. The changes of supply and demand properties are tracked using scenario-based approach. Of course, demand can be increased or decreased depending on the type of product. Here, each scenario captures the percentage of regular supply amount and market demand whose properties are characterized by the intensity of disruptions. We generate the values of demand and order fraction using the method of random number generation. A comprehensive description on the definition of scenario is found in Ali and Nakade (2014).

Lost sales: Our system, as a response policy, involves emergency ordering from a local (backup) supplier. In a situation when the emergency order exceeds the maximum permissible amount that could be ordered to the back-up supplier, the system observes lost sales.

This remainder of this chapter is organized as follows: Section 3.2 describes a brief explanation on Conditional Value at Risk (CVaR). Section 3.3 presents the problem statement. Section 3.4 focuses on mathematical formulation. Design implications for work are illustrated in Section 3.5. Section 3.6 presents a comparison of some results for a risk-neutral and risk-averse environment. Finally, Section 3.7 concludes the chapter.

3.2 Brief Description on Conditional Value at Risk (CVaR)

Conditional Value at Risk (CVaR) is an extension of Value at Risk (VaR). Value at Risk (VaR) is not able to assess the losses at the tail end of the distribution of losses whereas CVaR can quantify those losses. Mathematically speaking, for a given probability level, the $\beta - VaR$ of a portfolio expresses the lowest amount α such that the loss would not exceed α. On the other hand, the β-CVaR is the conditional expectation of losses above that amount α (Zongrun & Yanju, 2006). In other words, VaR computes the acceptable loss level of an asset or portfolio to an investor whereas CVaR is intended to mirror the losses exceeding VaR. Even though VaR is a very popular measure of risk in financial mathematics and financial risk management, many authors report that it contains some undesirable mathematical properties. Firstly, VaR calculates only percentiles of profit-loss distribution and ignores any loss beyond the VaR level (Artzner et al., 1997, 1999). Secondly, it lacks the properties of subadditivity and therefore it is not treated as a coherent risk measure (Artzner et al., 1997, 1999). Thirdly, Value at risk requires the use of binary variables which makes difficult to model VaR. However, it does not need to use binary variables to model CVaR concept. Besides, CVaR can be modeled using linear constraints (Catalão et al., 2012). Fourthly, VaR approach can`t easily incorporate scenarios (Zongrun & Yanju, 2006). As an alternative measure of risk, CVaR offers better properties than VaR (Artzner et al., 1997; Embrechts et al., 1999).

Some researchers (Embrechts et al., 1999; Pflug, 2000) prove that CVaR is a coherent risk measure which has some attractive properties such as transition-equivariant, positively homogenous, convexity, and monotonic. We entail a brief description on CVaR below following Rockafellar and Uryasev (2000). Interested readers are referred to

Rockafellar and Uryasev (2000) for more detailed descriptions on CVaR.

Let us consider a random variable $\mathrm{f}(\mathbf{x},\mathbf{y})$ which relates the loss to the decision vector **x.** The vector **x** is to be chosen from a certain subset **X** of $\Re^{\mathrm{n}}$, and the random vector **y** in $\Re^{\mathrm{m}}$. Here, the vector **x** denotes a portfolio, with **X** as the set of available portfolios subject to various constraints. The vector **y** represents the uncertainties that can affect the loss. For each **x**, the loss $\mathrm{f}(\mathbf{x},\mathbf{y})$ is a random variable that has a distribution in $\Re$ induced by the random vector **y.** Further**,** for convenience, the random vector **y** is assumed to have probability density function $\mathrm{P}(\boldsymbol{y})$. The probability of $\mathrm{f}(\mathbf{x},\mathbf{y})$ not exceeding a threshold α is given by

$$\Psi(\boldsymbol{x},\alpha) = \int_{f(x,y)\le\alpha} P(\boldsymbol{y})d\boldsymbol{y}.$$

As a function of α for fixed **x**, $\Psi(\boldsymbol{x},\alpha)$ is the cumulative distribution function for the loss associated with **x**. Rockafellar and Uryasev (200) state that the cumulative distribution function completely characterizes the behavior of this random variable. Moreover, it is noted that the function is fundamental in defining VaR and CVaR.

The $\beta - VaR$ and $\beta - CVaR$ values for the loss function associated with **x** with respect to a specified probability level β in (0,1) are denoted by $\alpha_\beta(\boldsymbol{x})$ and $\Phi_\beta(\boldsymbol{x})$ respectively. Thus, the following equations hold:

$$\alpha_\beta(\boldsymbol{x}) = min\,\{\alpha \in \Re :\ \Psi(\boldsymbol{x},\alpha) \ge \beta\}$$

and

$$\Phi_\beta(\boldsymbol{x}) = E\left[f(\boldsymbol{x},\boldsymbol{y})|f(\boldsymbol{x},\boldsymbol{y}) \ge \alpha_\beta(\boldsymbol{x})\right]$$

$$= \frac{1}{1-\beta}\int_{f(x,y)\ge\alpha_\beta(x)} f(\boldsymbol{x},\boldsymbol{y})P(\boldsymbol{y})d\boldsymbol{y}.$$

Since the VaR function $\alpha_\beta(\boldsymbol{x})$ is involved in the above equation, it is difficult to handle CVaR. To ease the computation process, Rockafellar and Uryasev (2000) define a function as follows:

$$F_\beta(\boldsymbol{x},\alpha) = \alpha + \frac{1}{1-\beta}\int[f(\boldsymbol{x},\boldsymbol{y}) - \alpha]^+ \, p(\boldsymbol{y})d\boldsymbol{y},$$

where

$$[t]^+ = \begin{cases} t & when\ t > 0, \\ 0 & \text{when t} \leq 0. \end{cases}$$

Then $\Phi_\beta(\boldsymbol{x}) = min_\alpha F_\beta(\boldsymbol{x},\alpha)$. If we don't find an analytical expression of this function, but we have S scenarios $(y_{1,}y_{2,} \dots \dots \dots y_s)$, sampled from density, for the random vector **y** with probability of each scenario $p(s)$, then the function $F_\beta(\boldsymbol{x},\alpha)$ can be approximated as below.

$$F_\beta(\boldsymbol{x},\alpha) = \alpha + \frac{1}{1-\beta}\sum_{s=1}^{S}[f(\boldsymbol{x},\boldsymbol{y_s}) - \alpha]^+ P_s.$$

We can simply write $[f(\boldsymbol{x},\boldsymbol{y_s}) - \alpha]^+$ as follows:

$[f(\boldsymbol{x},\boldsymbol{y_s}) - \alpha]^+ = Z_s$, where

$Z_s \geq f(\boldsymbol{x},\boldsymbol{y_s}) - \alpha,$

$Z_s \geq 0.$

In financial risk management literature, $f(\boldsymbol{x},\boldsymbol{y_s})$ represents the loss function of a portfolio. Of course, we could make other interpretations as well to apply the above approximation to other fields. For example, this may be a cost function in an optimization framework. A decision maker may be encouraged to examine the cost of high risk in a system by applying the Conditional Value at Risk (CVaR) approach. Hence, it is not unusual to think the function $f(\boldsymbol{x},\boldsymbol{y_s})$ as a cost function. For example, we can see Gotoh & Takano (2007), Catalão et al. (2012), Sawik (2011), Chen et al. (2009) to have an image on the application of this function in supply chain modeling. Finally, using scenarios, we have the linear programming (LP) formulation of the CVaR model in a simpler form as shown below.

Minimize $\quad \alpha + \frac{1}{1-\beta}\sum_{s=1}^{S} Z_s P_s,$

Subject to,

$Z_s \geq f(\boldsymbol{x},\boldsymbol{y_s}) - \alpha,$

$Z_s \geq 0.$

In the above formulation, Z_s is an auxiliary real variable. This variable is employed to compute CVaR. In fact, Z_s represents the amount by which cost in scenario s exceeds VaR. To summarize, Value at Risk (VaR) at a $100\beta\%$ confidence level is the target cost such that $100\beta\%$ of the cases, the outcome would not exceed VaR. Further, for the remaining 100 $(1-\beta)\%$ of the cases, the outcome may exceed VaR. On the other hand, Conditional Value at Risk (CVaR) at a $100\beta\%$ confidence level is the average cost in the worst $100(1-\beta)\%$ of the cases. This implies that $100(1-\beta)\%$ of the outcome exceed VaR and the mean value of these outcomes is defined as CVaR (Sawik, 2011).

3.3 Problem Statement

This chapter studies a supply chain consisting of multiple agents-outside suppliers, local supplier, and distributors as shown in Figure 3.1. There exists a central purchasing manager/decision maker who estimates the customer demand for each distribution center and would like to allocate the purchasing order to a given set of suppliers. One of the objectives of the decision maker is to minimize the relevant sourcing cost. The other objective is to minimize the effect of disruptions. A set of products are outsourced from a group of outside suppliers as well as the local supplier. These products are then distributed to customers through different distribution centers/depots/warehouses located at different regions in a territory. It is well known that the demand for a product largely depends on its own price and competing products' price. Besides, there are some other factors that influence market demand. Those factors, for instance, include the type of product, customer preferences, weather conditions, disasters, as well as locations. From our experience, we see that customers might share different levels of product demand in the event of disruptions signals or right after the occurrence of disruptions. For instance, customers want to buy more petroleum oil when they hear about Middle East instability. Moreover, note that due to disruptions in production and/or sourcing process of the suppliers, they are unable to supply an amount that was pre-scheduled during planning.

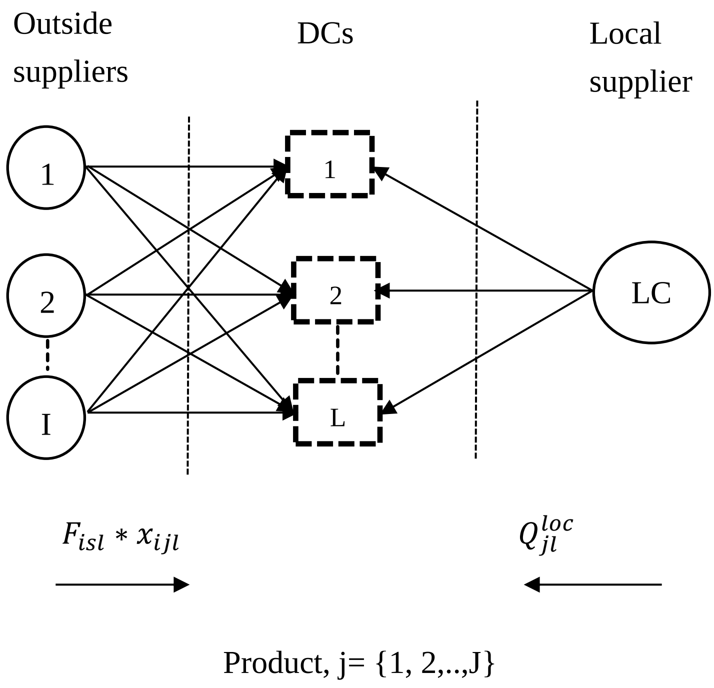

Fig. 3.1 The structure of the proposed supply chain

Certainly, disruptions impose a drastic change in supply and demand. In order to mitigate the impacts of disruptions, dual or multiple sourcing is an option which is more or less discussed in the supply chain risk management literature. The effectiveness and applicability of dual/multiple sourcing are discussed in Section 3.1. In this work, we furnish our modeling framework with multi-sourcing strategy. The system keeps a fixed and reliable local supplier having limited capacity. We think the outside supply source to be disruptions sensitive while the local supplier is free from disruption. Therefore, the local supplier acts as a backup supplier to mitigate the effect of disruptions imposed by outside suppliers. It is noticed that backup supplier obviously adds extra cost in the system. With this multiple sourcing environment, the decision such as ordering policies to a set of suppliers may be thought of as one of the important strategic issues for firms in a competitive market domain. Here, we make a tradeoff analysis between ordering policies to suppliers in pre- and post-disruption situation, and the related cost keeping disruptions in mind. Notice that we use a multi-multi allocation (MMA) approach that adds extra flexibility in dealing with supply chain disruptions management (Ali and Nakade, 2015).

In this chapter, a mathematical optimization framework is proposed to minimize Conditional Value at Risk (CVaR) for a multi-product multi-agent supply chain system with an intention of disruption management of firms. The framework takes into account the purchasing cost, inventory holding costs, emergency ordering cost, and lost sales cost. The proposed work provides output in terms of ordering quantities to selected suppliers in a pre-disruption and post-disruption situation while minimizing the risk of having extreme cost. To model extreme cost cases, a popular and vastly applied risk measure known as Conditional Value at Risk (CVaR) is adopted from finance literature. The risk measure is aimed at minimizing the expected worst-case cost of a system. The CVaR risk measure is particularly significant to a risk-averse decision maker who always thinks about extreme conditions to control risk in a business process.

In our model, the decision variables related to ordering portfolio are the initial order to outside suppliers, and, initial as well as an emergency order to the fixed local supplier. Ordering under emergency circumstances actually indicates one of the response mechanisms that a firm can easily apply to its supply chain with disruptions (Ali & Nakade, 2014). It is particularly important to notice that the capacity of outside suppliers is reduced due to disruptions. Therefore, outside suppliers can`t supply the pre-scheduled amount, rather they are able to supply some fraction of the initial order. On the other hand, the local supplier can maintain the committed supply. We attempt to capture this feature using a scenario-based approach. Based on the potential impact of unanticipated events to outside suppliers, a decision maker can estimate emergency order quantities to fill the demand of customers. Section 3.4 gives details on this.

To examine the change of response policies for a risk-neutral and a risk-averse decision maker, we minimize the expected total cost in the first place. Expected cost model includes the sum of procuring cost from the local supplier, and the expected purchasing, inventory, and lost sales cost. This cost is equal to the product of scenario probability P_s and the associated costs summed over all the scenarios S. For simplicity, we consider a single period model, in which products are consumed linearly over time. Thus, we use average inventory holding cost in this work.

In a nutshell, the objective of the proposed formulation is twofold. First, we minimize the expected cost. This model suits well for a risk neutral environment. Second, we intend to minimize the potential worst case cost measured as CVaR cost. This model is preferred for a risk-averse decision analysis. Both models would yield optimal ordering strategies and have the ability to tackle potential disruptions. Notice that CVaR model calculates Value at Risk (VaR) cost in this setting.

3.4 Model Formulation

This section at first identifies the notation and constraints used in this study. Then it presents the expected cost and CVaR model. Let I, J, L, S be the set of outside suppliers, items, distribution centers, and scenarios respectively. The decision variables are provided in Table 3.1. The parameters used in the model are given in Table 3.2. In the next, the constraints of the proposed model are given in Section 3.4.1; the analytical framework is presented in Section 3.4.2.

Table 3.1 The decision variables in the model

Decision Variables	***Descriptions***
x_{ijl}	Amount of item j ordered from supplier i at distribution center l, $i \in I, j \in J,$ and $l \in L$
Q_{jl}^{loc}	Amount of item j ordered from local supplier at distribution center l, $j \in J,$ and $l \in L$
Q_{jls}^{eme}	Emergency order placed for item j at distribution center l under scenario s. $j \in J, l \in L,$ and $s \in S$
I_{jls}	Inventory level of product type j in distribution center l under scenario s, $j \in J, l \in L,$ and $s \in S$
T_{jls}	Lost sales of product j at distribution center l under scenario s, $j \in J, l \in L,$ and $s \in S$
α	Value at Risk (VaR)
V_s	Auxiliary real variable employed to calculate CVaR/The amount by which cost in scenario s exceeds VaR (tail cost), $s \in S$

Table 3.2 The parameters in the model

Parameters	***Descriptions***
P_s	Probability of scenario s, $s \in S$
D_{jls}	Demand of item j in distribution center l in disruption scenario s, $j \in J, l \in L,$ and $s \in S$
H_{jl}	Unit inventory cost of product type j in distribution center l, $j \in J,$ and $l \in L$
INV_{jl}^{max}	Inventory limit at a distribution center for a product type in a scenario s, $j \in J, l \in L,$ and $s \in S$
c_{ijl}	Unit cost (in \$/unit) of item j quoted by supplier i to distribution center l, $i \in I, j \in J,$ and $l \in L$
C_{jl}^{loc}	Unit cost (in \$/unit) of item j quoted by fixed local supplier to distribution center l in normal condition, $j \in J,$ and $l \in L$
C_{jl}^{eme}	Emergency cost per unit (in \$/unit) to be added to unit cost quoted by local supplier in normal condition, $j \in J,$ and $l \in L$
ρ_{jl}	Lost sales cost per unit (in \$/unit) of product j from distribution center l, $j \in J,$ and $l \in L$
Q_{jl}^{minloc}	Minimum order to local supplier for a product type j at a distribution center, l in normal condition $j \in J,$ and $l \in L$
Q_{jls}^{maxloc}	Maximum order to local supplier for a product type j at a distribution center l under scenario, s $j \in J, l \in L,$ and $s \in S$
F_{isl}	Percentage of order supplied by the outside supplier i in disruption scenario s to distribution center l, $i \in I, s \in S,$ and $l \in L$
β	Confidence level/Probability of exceeding Value at Risk (VaR)

3.4.1 Constraints in the proposed model

Constraints are an integral part of a mathematical model. To manage scarce resources, a system needs to impose restriction on the decision variables. In the current study, the proposed model considers five types of constraints. Those are inventory constraints, emergency order constraints, supplier capacity constraints, lost sales constraints, and risk management constraints. Besides, there are some non-negativity and integrality conditions. The constraints are illustrated as follows.

Inventory constraints:

The inventory of product i at distribution center l in a scenario s is equal to the product received from local supplier plus incoming flows from outside suppliers. Notice that due to the impact of disruptions at outside suppliers, they can`t supply the pre-scheduled amount, x_{ijl}. Hence, the effect of disruptions is taken by the factor, F_{isl} which varies depending on the type and extent of disruptions. Furthermore, it also depends on the location of distribution centers and the distance of those from outside suppliers. Because, we feel that the mode of transportation may suffer disruptions, and as such, the goods carried by transportation vehicles are damaged or lost. Thus, we have the following equation:

$$I_{jls} = Q_{jl}^{loc} + \sum_{i \in I} F_{isl}\, x_{ijl,} \quad \forall j \in J, l \in L, s \in S.$$

The inventories are limited by their corresponding upper bound. The upper bound is fixed by the capacity of distribution centers to store a particular type of product.

$$I_{jls} \leq INV_{jls,}^{max} \qquad \forall j \in J, l \in L, s \in S.$$

Emergency ordering constraints:

Firms need to place an emergency order when there is a shortage of inventory to meet the demand of customers. The amount of emergency order is determined by the following equation. It is seen that emergency ordering policy is a function of demand and inventory in a scenario s.

$$Q_{jls}^{eme} \geq D_{jls} - I_{jls,} \quad \forall j \in J, l \in L, s \in S.$$

Supplier capacity constraints:

We assume that the outside suppliers have infinite capacity. On the contrary, the local supplier`s capacity is limited to supply each type of product to the distribution centers

(DCs). Thus, the ordering quantities to the local supplier in normal (Q_{jl}^{loc}) situation is restricted by the following constraint.

$Q_{jl}^{loc} \geq Q_{jl,}^{minloc} \qquad \forall j \in J, l \in L.$

Lost sales constraints:

Lost sales might happen in the system in a situation while the amount of emergency order exceeds the maximum amount $\left(Q_{jls}^{maxloc}\right)$ that can be ordered to local supplier. Thus, we take the following equation into account.

$T_{jls} \geq Q_{jls}^{eme} - Q_{jls,}^{maxloc}$ and $T_{jls} \geq 0, \qquad j \in J, l \in L, s \in S.$

Risk constraints:

For discrete scenarios, Conditional Value at Risk (CVaR) is mathematically defined as, $CVaR = \alpha + \frac{1}{1-\beta} \sum_{s \in S} P_s V_{s.}$

Subject to,

$V_s \geq f_s - \alpha, \quad \forall s \in S$, where f_s is the cost for each scenario s, and V_s is the auxiliary real variable to calculate CVaR; and

$V_s \geq 0, \quad \forall s \in S.$ This constraint fulfills the requirement for formulating a Conditional Value at Risk (CVaR) model.

Non-negativity and integrality conditions:

The following constraints are the non-negativity constraints related to the decision variables.

$x_{ijl}, Q_{jl}^{loc}, Q_{jls}^{eme}, I_{jls}, T_{jls} \geq 0, \qquad \forall i \in I,\ j \in J,\ l \in L,\ s \in S.$

$V_s \geq 0, \quad \forall s \in S;$ and $\alpha \geq 0.$

3.4.2 Proposed model

The model is subject to some assumptions listed below:

i. Local supplier is not subject to disruptions whereas outside suppliers are prone to disruptions. Therefore, outside supplier can`t supply a pre-scheduled amount.
ii. The lost sales cost per unit is greater than the sum of per unit procurement cost to the local supplier in emergency and normal situation. That is, $\rho_{jl} > \left(C_{jl}^{eme} + C_{jl}^{loc}\right)$.
iii. The model assumes a single period.
iv. Purchasing cost from the local supplier is greater than outside suppliers.

3.4.2.1 Minimization of expected cost

In a risk-neutral operating condition, a decision maker would like to minimize the total expected cost of a system. The following formulation would determine the ordering portfolio to the selected set of suppliers in a risk neutral supply chain environment.

$$Min\ Z = \sum_{j\in J}\sum_{l\in L} Q_{jl}^{loc} C_{jl}^{loc} + \sum_{s\in\in S} P_s \Big\{\sum_{i\in I}\sum_{j\in J}\sum_{l\in L} F_{isl}\, x_{ijl} c_{ijl} + \sum_{j\in J}\sum_{l\in L}\tfrac{1}{2} H_{jl} I_{jls} + \sum_{j\in J}\sum_{l\in L}\left(C_{jl}^{eme} + C_{jl}^{loc}\right) Q_{jls}^{eme} + \sum_{j\in J}\sum_{l\in L}\Big(\rho_{jl} - \left(C_{jl}^{eme} + C_{jl}^{loc}\right)\Big) T_{jls}\Big\}. \quad (3.1)$$

Subject to,

$$I_{jls} = Q_{jl}^{loc} + \sum_{i\in I} F_{isl}\, x_{ijl,} \quad \forall j \in J, l \in L, s \in S, \quad (3.2)$$
$$Q_{jls}^{eme} \geq D_{jls} - I_{jls,} \quad \forall j \in J, l \in L, s \in S, \quad (3.3)$$
$$I_{jls} \leq INV_{jls,}^{max} \quad \forall j \in J, l \in L, s \in S, \quad (3.4)$$
$$T_{jls} \geq Q_{jls}^{eme} - Q_{jls,}^{maxloc} \quad \forall j \in J, l \in L, s \in S, \quad (3.5)$$
$$Q_{jl}^{loc} \geq Q_{jl,}^{minloc} \quad \forall j \in J, l \in L, \quad (3.6)$$
$$x_{ijl,}\, Q_{jl,}^{loc}\, Q_{jls,}^{eme}\, I_{jls,}\, T_{jls} \geq 0, \quad \forall i \in I,\ j \in J, l \in L, s \in S. \quad (3.7)$$

Equation (3.1) is the objective function. It is comprised of five terms. The first term in the objective function specifies the sum of procurement cost related to local supplier. The second term expresses the expected cost for purchasing products from outside suppliers.

Then, the third term constitutes the expected inventory holding cost. The fourth term presents the expected emergency purchasing cost. Lastly, the fifth term stipulates the expected lost sales cost in the system. Equations (3.2)-(3.7) are explained in Section 3.4.1.

3.4.2.2 Minimization of CVaR cost/ worst-case cost

The following formulation would minimize the Conditional Value at Risk (CVaR) cost of our system, and determine the ordering portfolio to the selected set of suppliers. Note that the formulation would compute the Value at Risk (VaR) also. When we apply CVaR approach for risk management, it incorporates the magnitude of the tail cost. Therefore, the CVaR measure provides a more accurate estimate of the risks of higher cost (Sawik, 2011). In this research, the basic CVaR equation is formulated as an auxiliary function introduced by Rockafeller and Uryasev (2000). In a CVaR model, decision makers choose the value of confidence level, β. Different confidence level gives the different image of extreme cost. For example, for β=95% the CVaR computes the mean of the highest 5% of cost. For β=50% the CVaR evaluates the mean of the highest 50% of cost and so on. It is stated that the value of β also indicates the probability of exceeding Value at Risk (VaR) (Rockafeller and Uryasev, 2000; Sawik, 2011). By combining the aforesaid constraints and costs, we propose the CVaR optimization framework as follows:

$$Min\ CVaR = \alpha + \frac{1}{1-\beta} \sum_{s \in S} P_s V_s. \tag{3.8}$$

Subject to,

Equations (3.2)-(3.7), and

$$f_s = \sum_{j \in J} \sum_{l \in L} \frac{1}{2} H_{jl} I_{jls} + \sum_{j \in J} \sum_{l \in L} \left(C_{jl}^{eme} + C_{jl}^{loc}\right) Q_{jls}^{eme} + \sum_{i \in I} \sum_{j \in J} \sum_{l \in L} F_{isl}\, x_{ijl} c_{ijl} + \sum_{j \in J} \sum_{l \in L} Q_{jl}^{loc}\, C_{jl}^{loc} + \sum_{j \in J} \sum_{l \in L} \left(\rho_{jl} - (C_{jl}^{eme} + C_{jl}^{loc})\right) T_{jls}, \quad \forall s \in S, \tag{3.9}$$

$$V_s \geq f_s - \alpha, \quad \forall s \in S, \tag{3.10}$$

$$V_s \geq 0, \quad \forall s \in S, \tag{3.11}$$

$$\alpha \geq 0. \tag{3.12}$$

The objective function is expressed by Equation (3.8). It has two components. The first term in the objective function is actually the Value at Risk (VaR). For a given probability, Value at Risk (VaR) computes an amount of cost such that the supply chain system would never experience higher cost than the indicated VaR in a specified time horizon. The second term computes the average of those cost instances that exceed VaR. Equation (3.9) presents the cost function for our CVaR model. This function corresponds to the relevant cost components including purchasing cost during normal and emergency situation, average inventory holding cost, and lost sales cost. Constraint (3.10) imposes the condition to formulate the CVaR model. To model a CVaR approach, this constraint is important because it quantifies the amount that exceeds Value at Risk (VaR) in each scenario. Lastly, constraints (3.11)-(3.12) ensure the non-negative values of the respective decision variables.

3.5 Design Implications for Work

In this section, we design and implement a number of numerical experiments to test the proposed model. The model is validated for a simple supply chain. Let us consider a simplified representation of a supply chain consisting of two outside suppliers, one local supplier, and two distribution centers. Here, the decision maker outsources two categories of product at the distribution centers (DCs) from the three suppliers. To examine the performance of the model, several test instances are constructed by varying confidence level as well as supply and demand scenarios. In the analysis, we consider normal probability distribution for product demand and order fraction realization. Table 3.3 summarizes the range of data of the test problems. We only show the range for clarity. For each confidence level, we begin with 20 scenarios and continue the experiment up to 500 scenarios, with each having the same probability of occurrence. Table 3.4 presents these numerical instances, some results, as well as some features of the optimization framework. For simplicity, we assign the same probability of occurrence for each scenario in a test set. However, a decision maker may put different probabilities based on disruptions database and experience. We consider five confidence levels in our analysis. These are 0.5, 0.75, 0.90, 0.95 and 0.99. Thus, we aim to minimize the highest 50%, 25%, 10%, 5% and 1% of the cost. The results with the variations of confidence level and the number of scenarios are presented in Figure 3.2 and 3.3 respectively. The interpretations of the results are entailed later. To make the model more realistic, the data related to supply and demand with disruptions could be achieved from the historical information of disruptions database of a firm. Decision makers can use those benchmark values to check the model, or they can assume a probability distribution that better fits and characterizes those data. Unfortunately, it`s difficult to get real-life data from firms. However, many real world events could be described by normal distribution as it holds the natural variation of a system. As such, normally assumption is widely undertaken in the literature (Petkov & Maranas, 1989). In this work, we characterize the demand and the fraction of order realization as normally distributed random variable. Thus, we let *D~N(1500,500),* where mean demand is 1500 units, and standard deviation is 500. Similarly, the percentage of supply is attributed to mean 0.80, standard deviation 0.10 i.e. *F~N(0.80, 0.10).* Next, we generate and utilize random numbers to test the proposed model. Note that we have not mentioned any particular product type for which the range of data is fitted to. Rather, this model is expected to fit into consumer product categories in general. Note that this model could be retested and applied for any types of product by suitable modification of the parameters used here.

Table 3.3 Range of data for the test problems

Parameters	Range of data
Product demand	D~N(1500,500)
Fraction of order/ outside	F~N(0.80,0.10)
Purchasing cost/outside ($)	[7,9]
Purchasing cost/local ($)	[10,13]
Inventory cost ($)	[1,2]
Emergency cost ($)	[12,14]
Lost sales penalty cost ($)	[200,285]
Ordering limit/local	[600,50000]
Inventory Limit	[20,000]

Table 3.4 Estimates of CVaR from minimum CVaR approach for different number of scenarios with different confidence level

Confidence level, β	# of scenarios	Optimum CVaR ($)	# of iterations	# of variables	# of equations	CPU time (seconds)
0.50	20	79906	78	294	365	2.091
	50	79899	172	714	905	5.132
	100	82550	349	1414	1805	10.218
	300	83929	951	4214	5405	31.184
	500	82946	2661	7014	9005	50.794
0.75	20	83738	66	294	365	2.106
	50	84317	176	714	905	5.132
	100	87519	313	1414	1805	10.218
	300	89101	926	4214	5405	30.436
	500	88060	2045	7014	9005	50.856
0.90	20	85796	73	294	365	2.106
	50	88043	123	714	905	5.133
	100	94064	392	1414	1805	10.202
	300	94859	874	4214	5405	30.591
	500	93520	1889	7014	9005	50.444
0.95	20	85796	58	294	365	2.106
	50	89577	147	714	905	5.148
	100	98967	279	1414	1805	10.156
	300	98057	648	4214	5405	30.608
	500	97489	2192	7014	9005	50.654
0.99	20	85796	61	294	365	2.106
	50	89577	162	714	905	5.132
	100	101000	323	1414	1805	10.218
	300	105061	682	4214	5405	30.498
	500	104889	1741	7014	9005	50.638

The mathematical model presented in this chapter is a linear programming (LP) formulation. Linear programming (LP) problem is attractive to many researchers due to the ease of computation by utilizing available software. The solvability of a model is very important in order to apply the model for a real-life decision environment. In our work, the problem is coded on GAMS 24.1.3 and run by CPLEX 12.5.1.0 solver on an Intel (R) Core (TM) i7-3770 Dual Processor with 24GB RAM and a 3.40GHz CPU. According to Table 3.4, the model converges rapidly and produces output. The numbers of iterations taken to converge to optimum solution as well as number of individual equations and variables are also registered in Table 3.4. For higher number of scenarios, the number of equations and variables increase. As a result, computation times also increase as seen in Table 3.4.

Figure 3.2 displays the nature of CVaR cost with the number of scenarios for a given confidence level. It is mentioned earlier that the confidence level is set at five levels of 0.5, 0.75, 0.90, 0.95 and 0.99 to perform the numerical experiment. As shown in Figure 3.2, for a given confidence level, the CVaR cost increases with the increase of number of scenarios up to a certain level. After that, it shows a slightly decreasing trend. As the sum of all scenario probabilities equals one, the average CVaR cost tends to become lower for higher number of scenarios. In Ali and Nakade (2014, 2015), the expected cost versus number of scenarios graph also presents a somewhat similar pattern. In addition, the CVaR cost is higher for higher confidence level as charted in Figure 3.2. According to Figure 3.2, the highest CVaR cost is obtained at confidence level 0.99. For confidence level 0.99, the CVaR model enumerates the average of the highest 99% cost. Thus, the highest CVaR cost is achieved in this case. Note that our experiment is limited to the S equally probable scenarios for every test instance. However, one could construct and include scenarios with different probabilities in the same model.

Figure 3.3 plots the variation of CVaR measure with different confidence levels under a given number of scenarios. The figure represents how the CVaR cost is sensitive to the confidence levels chosen by a decision maker. According to Figure 3.3, the CVaR cost increases with an increment of confidence level for most of the cases. It is owing to the fact that for a higher confidence level, the CVaR approach estimates the average of those high cost instances exceeding the confidence level. Thus, a rise in CVaR cost with respect to a given number of scenarios is depicted in Figure 3.3.

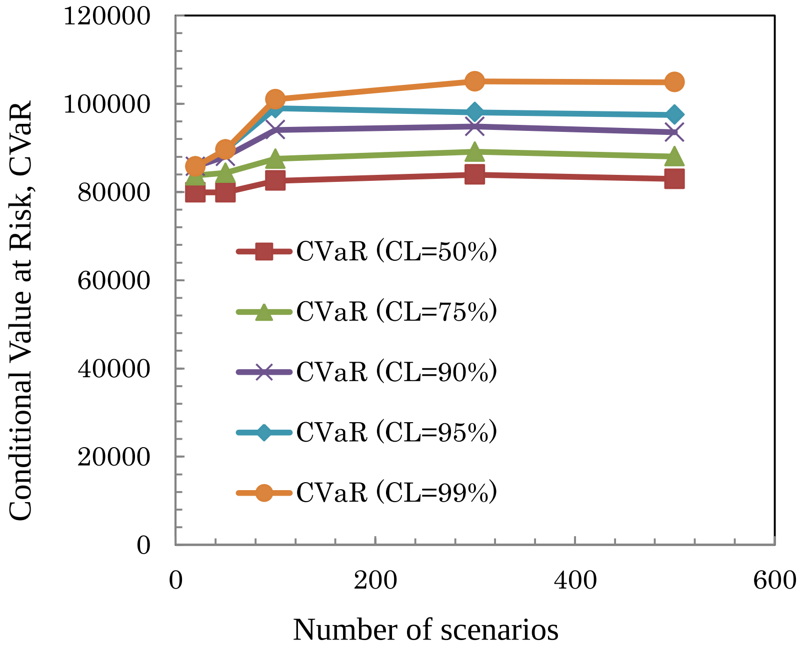

Fig. 3.2 The variation of CVaR with number of scenarios

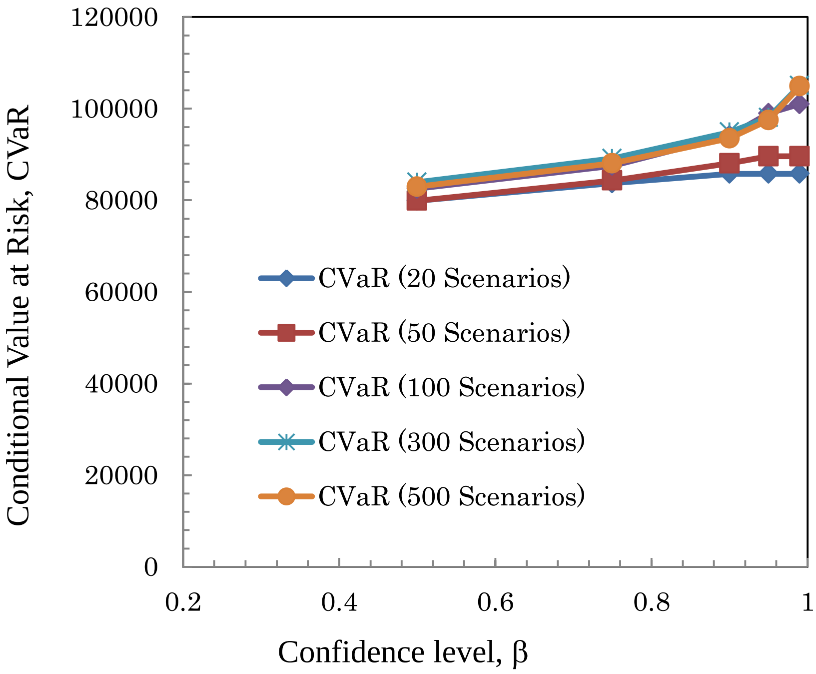

Fig. 3.3 The change of CVaR with confidence level

3.6 Comparison of Results: Risk-averse and Risk-neutral Decision Making

From risk management viewpoint, there are two types of decision making policies existed in supply chain system. Those are named risk-neutral and risk-averse policies. In risk-neutral system, the decision maker considers those policies so as to minimize expected cost. However, a risk-averse decision maker tends to minimize worst-case cost. In this section, we present some results of the CVaR and the expected cost model. Here, decisions on ordering quantities to the local and outside suppliers in normal and disrupted condition for a risk-neutral and risk-averse decision maker are computed. For a given confidence level, we perform numerical experiment to minimize the CVaR cost. We repeat the experiment for different confidence level. We also investigate the expected cost minimization approach. The results under both approaches are presented in Table 3.6, 3.7 and 3.8. The results clearly highlight the effect of varying cost and risk preference for a decision maker in a supply chain. We consider 100 scenarios in this analysis but for reasons of clarity we mention few results. The optimum cost obtained in the expected cost model is equal to $76,186. Further, the solution results in terms of cost for CVaR model are given in Table 3.5.

We observe that CVaR and VaR tend to increase with the increase of confidence level. However, we see that CVaR=VaR=$101000 for the confidence level 0.99. The reasons behind this observation is that when the highest cost probability is greater than 1-β, then CVaR and VaR are identical with the highest cost. Similar results are reported in the work of Sawik (2011).

From Table 3.6 it is seen that the ordering quantities are the same irrespective of the confidence level used in the CVaR model. As reported in Table 3.6, the expected cost model also produce the same values of ordering quantities. This might be due to the fact that the minimum ordering quantities to the local suppliers are to be placed before disruptions and these variables are independent of disruptions scenarios. We use one constraint equation to ensure this. Thus the results illustrate minimum quantities which are actually an intuitive observation.

Table 3.5 Solution results (cost) for CVaR model

Confidence level	0.75	0.90	0.95	0.99
CVaR	87519	94064	98967	101000
VaR	79769	86507	94251	101000

Table 3.6 Order quantities to local supplier in minimizing CVaR and total expected cost

Decision variables (Q_{jl}^{loc})	Solution obtained (CVaR model)				Solution obtained (expected cost model)
	Confidence level				
	0.75	0.90	0.95	0.99	
J1L1	600	600	600	600	600
J1L2	600	600	600	600	600
J2L1	600	600	600	600	600
J2L2	600	600	600	600	600

Table 3.7 Order quantities to outside supplier in minimizing CVaR and total expected cost

Decision variables (x_{ijl})	Solution obtained (CVaR model)				Solution obtained (expected cost model)
	Confidence level				
	0.75	0.90	0.95	0.99	
I1J1L1	1178.797	177.932	1943.347	1943.347	93.525
I1J1L2	1735.320	2041.672	1957.188	1865.682	1509.00
I1J2L1	1241.149	1769.993	1756.730	0	434.770
I1J2L2	1149.283	1993.272	2338.009	1147.738	1103.680
I2J1L1	470.837	1591.826	0	0	1278.682
I2J1L2	0	0	0	0	0
I2J1L1	401.150	0	0	2263.480	1032.772
I2J2L2	725.845	0	0	1341.852	328.888

Table 3.7 shows the ordering portfolio to the selected set of outside suppliers. The required amounts are distributed and diversified to different suppliers based on supply disruptions factor, inventory amount, as well as other factors such as costs of products. We don't observe any stable pattern for the ordering portfolio to outside suppliers. Surprisingly, for some instances, some degrees of instability are observed when switching from one confidence level to other. As illustrated in Table 3.7, for I2J1L1 and I2J2L2, no quantities are ordered at confidence level 0.90 and 0.95. When we relax continuous distribution and model CVaR as a discrete distribution of cost, it might have different impact on the optimal portfolio. Such instability arises due to the discontinuity in the distribution function or due to the concentration of a large probability atom at some cost (Sawik, 2011).

Table 3.8 Emergency order quantities in minimizing CVaR and Total expected cost

Decision variables (Q_{jls}^{eme})	Solution obtained (CVaR model)				Solution obtained (expected cost model)
	0.75	0.90	0.95	0.99	
J1L1S1	389.983	390.499	125.216	125.216	670.145
J1L1S2	0	0	0	0	0
J1L1S3	185.418	92.003	0	0	382.664
J1L1S4	0	0	0	0	0
J1L1S5	44.678	0	0	0	75.915
J1L1S6	100.115	0	0	0	246.885
J1L1S7	0	0	0	0	0
J1L1S8	0	0	0	0	0
J1L1S9	0	0	0	0	135.112
J1L1S10	0	0	0	0	0
J1L1S11	0	0	0	0	115.015
J1L1S12	0	0	0	0	298.533
J1L1S13	297.165	86.909	144.539	144.539	400.461
J1L1(S14- S21)	0	0	0	0	0
J1L1S22	676.073	633.954	392.413	392.413	964.432
J1L1S23	0	0	0	0	0
J1L1S24	0	0	0	0	0
J1L1S25	0	0	0	0	0

Notice that in the literature and in practice, most commonly used confidence level varies between 0.90 to 0.99 (Conejo et al., 2008). However, we apply the other confidence level ($\beta=0.75$) for analysis purpose. In fact, a decision maker becomes more risk-averse with the increase of confidence level. Thus he focuses on a smaller set of extreme outcomes. For a smaller set of outcomes, identical results might be observed. It is pointed out that due to giving much attention on worst cost scenario in modeling CVaR, this process asks for lesser amount of emergency order than the expected cost minimization approach. Another explanation might be due to the fact that if the highest cost probability is greater than $1-\beta$, CVaR is equal to VaR and are identical with the highest cost. In this event, for a higher confidence level β, lower amount of emergency quantities are computed by the CVaR model. Interested readers are referred to Sawik (2011) for details. It is also noted in Table 3.8 that there are some cases, in which no emergency order is placed irrespective of the model. We think that the solutions are based on supply and demand scenarios. We restrict our discussions to a limited number of observed results. The interpretation might be different for an infinite number of scenarios. For generating an infinite number of scenarios, in particular for multi-stage linear programming, MonteCarlo method could be applied in the future work. MonteCarlo method is very popular to researchers for modeling stochasticity in many fields including supply chain risk management (Monforti & Szikszai, 2010; Schmitt & Singh, 2009). Interestingly, intelligence approach such as Artificial Neural Network (ANN) could also be applied for generating data for the purpose of modeling stochasticity of parameter (Vagropoulos et al., 2013).

3.7 Conclusions

This chapter proposes a Conditional Value at Risk (CVaR) model for the selection of supply portfolio in a multi-product multi-supplier supply chain subject to supply and demand disruptions. Importantly, the model illustrated in this work is intended to minimize the risk of higher cost in the supply chain system. Cost such as inventory holding cost, purchasing cost, emergency ordering cost, and lost sales cost are included in the framework. The model is tested by applying a number of confidence levels-0.75, 0.90, 0.95 and 0.99. These confidence levels actually indicate the attitude of decision maker towards risk. The results indicate that ordering policies are highly sensitive to the risk attitude of decision maker, as well as supply and demand scenarios. It is also seen that the ordering portfolio in the CVaR model shows considerable difference compared to the expected cost model. Thus, like financial risk management, the CVaR approach may find the applicability and significance to minimize the worst-case cost of a supply chain system.

We so far integrate supply and demand disruptions with a focus on risk-neutral and risk-averse decision making perspective in Chapter 2 and Chapter 3 respectively. One interesting research direction may be to build a supply chain disruptions management framework by incorporating supply and storage facilities disruptions. We focus on this issue in Chapter 4.

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Chapter 4

A Mathematical Optimization Approach to Supply Chain Disruptions Management Considering Disruptions to Suppliers and Distribution Centers

4.1 Introduction

In recent times, supply chain disruptions management has gained enormous attention from researchers and practitioners in the competitive business domains. Any events or collection of events that prevent a supply chain network from its regular operations might be defined as disruptions. Whatever might be the nature and magnitude of a disruption, it produces undesirable effects. For example, it might stop shop floors/distribution centers/warehouses from their day to day operations. In addition, it might stop flow of goods from one point to another in a network. Moreover, the on-hand raw material or finished products might be damaged due to disruptions. Therefore, disruptions hamper the entire plan of an organization thereby causing financial and reputational losses (Paul et al., 2014). Furthermore, it is advocated that designing a proper supply chain network is extremely important in order to facilitate overall business operations of an organization successfully (Chatzipanagioti at al., 2011). However, a well-designed supply chain might not perform up to its standard because of the presence of uncertainty (Wang & Abareshi, 2014) and risks in the chain. Supply chain risks appear in a diversified nature on the different parts of a chain. Of all the various types of risks discussed in supply chain literature (Chopra & Sodhi, 2004; Heckmann et al., 2015; Ma et al., 2010; Tang, 2006; Vilko & Ritala, 2014), supply chain disruption risk is one of them. The interesting concept of disruptions management is firstly articulated by Clausen et al. (2001). They successfully apply the idea to airlines industry to resolve airline flight and crew scheduling problems. Next, the concept of disruption management appears for a wider range of applications such as production planning (Yang et al., 2005), machine scheduling (Qi et al.,2006), project scheduling

(Zhu et al., 2005), logistics network design (Rusman & Shimizu, 2013), supply chain network design (Taha et al., 2014), and supply chain management (Qi et al., 2004).

Of recent, the widely accepted philosophy of lean inventory management makes the supply chain network of an enterprise sensitive and vulnerable to disruptions (Garcia-Herrerros et al., 2013). Hendricks and Singhal (2005) report that supply chain disruptions has long term negative impacts on the supply chain financial performance. Further, a recent report by World Economic Forum shows that supply chain disruptions cut the share price of impacted companies by 7% on average (Bhatia et al., 2013). A very well-known example that highlights supply chain disruptions and effective response strategy is the case of Nokia-Ericsson in 2000. The Philip`s microchips plant was shut down due to a fire accident. It caused Ericsson loss for about $400 million, while Nokia managed to source from alternative suppliers thus minimized the disruption effect (Latour, 2001). In the last decade, the word experiences a series of natural disasters. The disasters show an escalating effect on the deterioration of the global supply chain performance. In 2013, 330 natural disasters were reported with huge economic impact (Guha-sapir et al., 2013). Actually, some high profile disasters that disrupt supply chain globally and force decision makers to think about supply chain disruptions are Hurricane Katrina and Rita in 2005, Indian Ocean earthquake and tsunami 2004, Japan earthquake and tsunami 2011, terrorist attacks 9/11 (Ali & Nakade, 2014; Lawrence et al., 2015).

There are some studies that recognize the effect and importance of considering disruptions in supply chain (Chopra & Sodhi, 2004; Craighead et al., 2007; Kim et al., 2015; Rice Jr & Caniato, 2003). They emphasize on risk handling strategies into the supply chain design. Despite the fact that managing supply chain disruptions are increasingly important in managing business resilience and continuity (Ambulkar et al., 2015; Falasca et al., 2008), little academic literature addresses the issues vibrantly thus far. In recent years, some authors suggest dual and/or multiple sourcing as one of the effective strategies to cope with supply chain disruptions risk (Ali & Nakade, 2014; Kelle & Miller, 2001; Parlar & Perry, 1996; Tomlin, 2006; Xia & Matsukawa, 2014;

Xiaoqiang & Huijiang, 2009; Yu et al., 2009). Right after the Japan disasters in 2011, the drive towards multiple sourcing from traditional single sourcing strategy has been started in practice to the decision makers in the area of supply chain operations. Though multiple sourcing strategies offer higher reliability in the supply chain of an enterprise, it adds more cost (Moritz & Pibernik, 2008). Traditional supply chain design problems deal with the issues of facility location problems (FLP) (Carlo et al., 2012; Lee et al., 2010; Melo et al., 2009; Raftani-amiri et al., 2010; Shariff et al., 2010).

The theory of the location of industries is proposed by Weber and Friedrich (1929). Since then, facility location problems (FLP) get enormous attention to the researchers as shown from the review articles (Meixell & Gargeya, 2005; Owen & Daskin, 1998; Shen, 2007) and some of the recent works on FLP (Bieniek, 2015; Dantrakul et al., 2014; Ho, 2015; Kim 2013; Lazic et al., 2010). In traditional supply chain design, it is assumed that the facilities will always remain in operation to provide service to customers. However, disruptions to the entities of a supply chain system are very common and almost inevitable in a complex and interdependent networks (Ali & Nakade, 2014; Hishamuddin et al., 2014; Medal et al., 2014; Schmitt & Singh, 2012). Despite the ever increasing importance of emphasizing disruptions in decision making of an organization, studies on facility location problems considering disruptions risks are few in supply chain literature.

Some authors investigate and link facility disruptions in the facility location problems in recent times. Azad et al. (2013) study the design problem of a reliable stochastic supply chain network. They consider random disruptions in the location of DCs and the transportation modes. They mitigate the effect of disruption through transporting goods from non-disrupted DCs to disrupted DCs. Baghalian et al. (2013) develop a mathematical formulation for a multi-product multi-echelon supply chain considering disruptions in manufacturers, distribution centers and their connecting links. Cui et al. (2010) formulate a mixed integer programming model and a continuum approximation model to study the reliable uncapacitated fixed-charge location problem (UFLP). They minimize the initial setup cost and the expected transportation cost in normal and failure scenarios. Snyder & Daskin (2005) formulate a reliability models based on the P-median problem (PMP) and the uncapacitated fixed-charge location problem (UFLP). They minimize operating cost while taking into consideration the expected transportation cost after failure of facilities. They apply Lagrangian relaxation algorithm to solve the model. Atoei et al. (2013) offer a supply chain network design model considering disruptions risk in both distribution centers and suppliers. Their model determines optimal location of distribution centers, assignment of customers and suppliers to non-disrupted DCs and transporting goods from non-disrupted DCs to disrupted DCs in the event of disruptions. Further, they model reliability of DCs in the work. In addition, Jabbarzadeh et al. (2012) design a supply chain network and formulate a nonlinear mixed integer programming model to incorporate facility disruptions. Their model determines facility location decisions, customer allocation decisions and cycle order quantities at facilities. They follow single sourcing strategy in their framework.

Ghomi-Avili et al. (2013) study facility failures and breakdown thus linking facility location with the disruptions risk of a supply chain that procures and distributes a single product. They classify the distribution centers as reliable and unreliable categories. In their work, the unreliable distribution centers are subject to failures. They solve the mathematical model using CPLEX and simulated annealing algorithm. Li et al. (2013) study the design of a reliable facility location problem considering heterogeneous facility failure probabilities. They formulate two nonlinear models: a reliable *P*-median problem (RPMP) and a reliable uncapacitated fixed-charge location problem (RUFL). They solve the models using Lagrangian relaxation (LR) approach and a myopic policy approach. They apply one layer supply backup in the models, and aim to fortify most reliable facilities regardless of demand topology. Garcia-Herreros et al. (2014) propose a two-stage stochastic programming formulation for the design of resilient supply chains with facility disruptions. They minimize the sum of investment cost and expected distribution cost. Their formulation determines the location and storage capacity of distribution centers, as well as distribution strategy. They apply multi-cut benders decomposition algorithm to solve the model.

Some other works that address designing supply chain networks or logistics networks with focusing on facility disruptions including Hatefi et al. (2014), Teimuory et al. (2013), Rafiei et al. (2013) etc. All these work show the importance of considering facility disruptions to timely respond to customer needs in adverse circumstances. Thus, facility disruption is becoming one of the widely studied topics in supply chain.

In view of the perspectives of risk concern supply chain architecture, this chapter addresses the design of a multi-product multi-echelon supply chain consisting of multiple suppliers, multiple distribution centers and multiple customers while focusing on disruptions risk. In most of the supply chain literature discussed above, single sourcing strategy with disruptions to suppliers or distribution centers is adopted. In this work, we follow multi-sourcing strategy in both procurement and distribution decisions. Hence, our work provides a multi-multi allocation (MMA) model in practice.

Moreover, we consider disruptions to suppliers and distribution centers. The goal of our work is to build a risk concern supply chain optimization framework considering disruptions risk in a multi-echelon supply chain environment. The problem determines the location of distribution centers and establishes a procurement and distribution strategy while taking into consideration the potential disruptions at the DC locations and the suppliers. The cost considered here is the investment cost in locating/renting DCs, the transportation cost in procurement and distribution of products, and the expected shortage cost in the case of possible disruptions.

For a better understanding of the optimization framework, a definition of the different terms used in this chapter is given below:

Disruptions: Any form of events/irregularities that hamper normal operation of a supply chain system. These events might include machine shutdown/machine breakdown, labor strike, natural disasters, and accidents in production, storage or transportation facilities etc.

Scenarios: While disruptions happen in any supply chain system, it negatively affects the system. The system therefore cannot respond as in the case of normal operating conditions. We say that when disruptions take place at the production facilities and storage/delivery facilities, those can`t supply the regular amount to their downstream side. To capture this effect, we consider several scenarios. Under a disrupted condition, each scenario expresses the percentage of normal supply amount in the system. Scenario based analysis on supply chain risk/disruptions management is found in Ali and Nakade (2014), Klibi & Martel (2012), Madadi et al. (2012), Thekdi & Santos (2015) etc.

Shortage cost: In our system, the distribution centers receive goods from the suppliers. Then the products undergo some operations like labelling and packaging and then those are carried to the customers (retailers). Due to disruptions to the suppliers or at the distribution centers (DCs), the distribution centers (DCs) can't meet the demand of the customers. We model this as a shortage penalty cost for unsatisfied demand. It is noted that this might be a lost sales cost or the cost of purchasing the products from a local supplier. The concept of keeping a backup supplier is found in the work of Ali & Nakade (2014), Hou et al. (2010), Huang et al. (2012), Qi (2013) etc.

The rest of the chapter is organized as follows. Section 4.2 describes the problem statement. Section 4.3 states the mathematical formulation. Section 4.4 illustrates the related computational experiment. Finally, Section 4.5 draws conclusion of the chapter.

4.2 Problem Statement

This chapter involves the formulation of an optimization framework of a multi-product, multi-echelon supply chain subject to supply and storage facility disruptions. The supply chain consists of multiple suppliers, one or more distribution centers (DCs), and multiple customers as shown in Figure 4.1. A family of products ($l \in L$) is outsourced from multiple suppliers ($i \in I$) and then shipped to the distribution centers ($j \in J$). Afterwards, the received products are shipped from the distribution centers to the customers ($k \in K$). Our problems involve selecting DCs among a set of candidate locations, the number of DCs to be selected and establishing distribution strategy while considering disruptions at the location of distribution centers (DCs) and to the suppliers. In this analysis, two assumptions are made herein. First, it is assumed that each and every distribution centers can receive products from each of the suppliers considered here. Second, each customer receives products from each of the distribution centers. Therefore, the supply chain is following a multi-multi allocation (MMA) strategy in both procurement and distribution of the products. The objective of our work is to minimize the sum of investment cost, the transportation cost and the expected shortage cost in the event of disruptions. We further assume that the supplies from the suppliers and from the DCs are partially disrupted while disruptions happen. In addition, it is pointed out that while disruptions happen to the suppliers, the products received to the distribution centers in the subsequent time periods would be lower than the regular flow amount. By the time period when the system is recovered from disruptions, the suppliers start to supply the regular flow amount. Further, while suppliers and DCs are disrupted, the system cannot meet all the demand of the customers. In this case, the system might incur shortage cost for unsatisfied demand. This cost might be a lost sales cost or the cost of purchasing the products from a local supplier during disruptions. It is noted here that we are not interested to explore the cases of complete failure of suppliers and/or facilities that might turn out a supply chain to be out of service partially or totally thus imposing a threat on organizational existence.

In our work, a scenario-based approach is followed to track the reduction in supplies of the suppliers and the distribution centers (DCs). The values of reduction in supplies are generated from normal distribution. Each scenario specifies the percentage of supply that is supplied from the suppliers and from the distribution centers to the downstream supply chain when the system suffers disruptions. Based on these observations, the amount of unsatisfied demand and the associated shortage cost are determined. The scenario probability is generated as a uniformly distributed random parameter. The expected shortage cost is evaluated by multiplying the scenario probability to the associated shortage cost summed over all the scenarios.

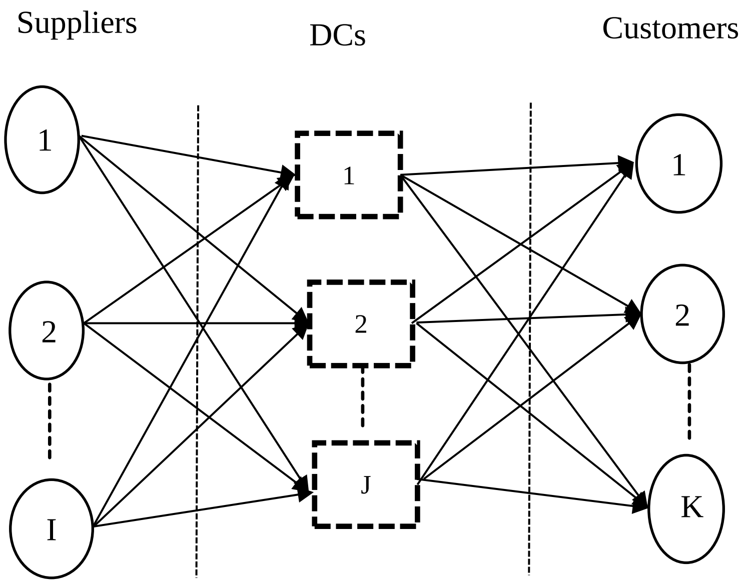

Fig. 4.1 The schematic diagram of a multiproduct multi-echelon supply chain

4.3 Model Formulation

This section at first highlights the sets, variables, and parameters used in the current study. Next, the assumptions to the mathematical formulation are mentioned. Then, the costs associated in the model are discussed. This section is closed by presenting the mathematical model, which is followed by an explanation of the constraints used in the model.

The index sets, variables, and parameters used in this chapter are as follows:

Sets

I	index set of suppliers i
J	index set of candidate locations for j DCs
K	index set of customers k
L	index set of commodities l
S	index set of scenarios s

Variables

X_j	Binary variable deciding whether DC at candidate location j is selected
Z_{ijl}	Amount of commodity l shipped from supplier i to DC j
y_{jkl}	Amount of commodity l shipped from DC j to customer k
Q^1_{jkls}	Amount of shortage of commodity l for customer k at DC j at first time period in scenario s
Q^2_{jkls}	Amount of shortage of commodity l for customer k at DC j at second time period in scenario s
y^2_{jkls}	Amount of commodity l for customer k that is supplied from DC j at second time period in scenario s

Parameters

D_{kl}	Demand of customer k for commodity l per time period
F_j	Fixed investment cost of DC j per time period
A_{ijl}	Transportation cost per unit of commodity l from supplier i to DC j
B_{jkl}	Transportation cost per unit of commodity l from DC j to customer k
Cap_j	Storage capacity of DC j
P_i	Production capacity of supplier i
π_s	Probability of scenario s
α_{isl}	A fraction of supply from supplier i of product l in scenario s. $\forall\, i \in I, l \in L, s \in S$
β_{jsl}	A fraction of supply from DC j of product l in scenario s. $\forall\, i \in I, l \in L, s \in S$
n_l	Space requirement rate of product l
m_l	Capacity utilization rate of product l
γ_{lk}	Penalty cost per unit of unsatisfied demand of product l for customer k
R	The number of distribution centers required to be located

Model assumptions

The assumptions associated with the model are listed below:

(a) Suppliers are not reliable and their production capacities are limited.

(b) Distribution centers storage capacities are limited.

(c) Suppliers and customers` locations are fixed. The distribution centers are required to be located.

(d) Demand is stochastic and uniformly distributed.

(e) The magnitude of disruptions is such that suppliers and distribution centers can't supply the regular flow amount in the event of disruptions. The percentage of supply from the suppliers and the distribution centers subject to disruptions is stochastic and follows a random normal distribution.

Mathematical model:

The minimization of the total cost comprises the following parts of the objective functions:

1. The total fixed cost for locating/renting distribution centers is given by the term:

   $\sum_{j \in J} F_j X_j.$

   This fixed cost is assumed as the cost incurred per unit time period. For example, the cost of renting a facility for a day/week/month etc.

2. The cost of shipping goods from multiple suppliers to multiple distribution centers (DCs), and from multiple distribution centers (DCs) to multiple customers. Every supplier can ship goods to each of the distribution centers. Further, every distribution centers can ship goods to each of the considered customers. Transportation cost is calculated by multiplying unit transportation cost to the amount of products shipped. The cost thus becomes

   $\sum_{i \in I} \sum_{j \in J} \sum_{l \in L} Z_{ijl} A_{ijl} + \sum_{j \in J} \sum_{k \in K} \sum_{l \in L} y_{jkl} B_{jkl}.$

3. The expected shortage cost in the event of disruptions is given by the following two terms. The first term represents the expected shortage cost in the first time period due to disruptions at the distribution centers. On the other hand, the second term represents the expected shortage cost in the second time period. Due to disruptions

to the suppliers in the first time period, the amount of products received at the distribution centers in the second time period would be lower than the regular amount. The shortage cost is calculated by multiplying unit shortage cost to the shortage amount in the first and second period. The expected shortage cost equals the product of the scenario probability and the associated shortage cost summed over all the scenarios considered.

$$\sum_{s\in S} \pi_s \begin{Bmatrix} \sum_{j\in J}\sum_{k\in K}\sum_{l\in L}\gamma_{lk}\, Q^1_{jkls} \\ +\sum_{j\in J}\sum_{k\in K}\sum_{l\in L}\gamma_{lk} Q^2_{jkls} \end{Bmatrix}.$$

Thus, the optimization problem is formulated as follows:

$$Minimize\ u =$$

$$\sum_{j\in J} F_j\, X_j + \sum_{i\in I}\sum_{j\in J}\sum_{l\in L} Z_{ijl}\, A_{ijl} + \sum_{j\in J}\sum_{k\in K}\sum_{l\in L} y_{jkl}\, B_{jkl} \ +$$

$$\sum_{s\in S} \pi_s \begin{Bmatrix} \sum_{j\in J}\sum_{k\in K}\sum_{l\in L}\gamma_{lk}\, Q^1_{jkls} \\ +\sum_{j\in J}\sum_{k\in K}\sum_{l\in L}\gamma_{lk} Q^2_{jkls} \end{Bmatrix}. \tag{4.1}$$

Subject to,

$$\sum_{j\in J} X_j = R, \tag{4.2}$$

$$\sum_{i\in I} Z_{ijl} = \sum_{k\in K} y_{jkl}, \quad \forall j \in J, l \in L, \tag{4.3}$$

$$\sum_{i\in I}\sum_{l\in L} Z_{ijl} \le MX_j, \quad \forall j \in J, \tag{4.4}$$

$$\sum_{k\in K}\sum_{l\in L} y_{jkl} \le MX_j, \quad \forall j \in J, \tag{4.5}$$

$$\sum_{j\in J} y_{jkl} = D_{kl}, \quad \forall l \in L, k \in K, \tag{4.6}$$

$$\sum_{l\in L} m_l \sum_{j\in J} Z_{ijl} \le P_i, \quad \forall i \in I, \tag{4.7}$$

$$\sum_{l\in L} n_l \sum_{k\in K} y_{jkl} \le Cap_j X_j, \quad \forall j \in J, \tag{4.8}$$

$$\sum_{j\in J} Q^1_{jkls} \ge D_{kl} - \sum_{j\in J}\left(\beta_{jsl} * y_{jkl}\right), \quad \forall l \in L, k \in K, s \in S, \tag{4.9}$$

$$\sum_{j\in J} Q^2_{jkls} \ge D_{kl} - \sum_{j\in J} y^2_{jkls}, \quad \forall l \in L, k \in K, s \in S, \tag{4.10}$$

$$\sum_{k\in K} y^2_{jkls} = \sum_{i\in I} \alpha_{isl} * Z_{ijl}, \quad \forall l \in L, k \in K, s \in S, \tag{4.11}$$

$$X_j \in \{0,1\}, \quad \forall j \in J, \tag{4.12}$$

$$y_{jkl}, Z_{ijl}, Q^1_{jkls}, y^2_{jkls} \ge 0, \quad \forall j \in J, l \in L, k \in K, s \in S. \tag{4.13}$$

Equation (4.1) is the objective function. It minimizes the sum of investment cost at DCs, the sum of distribution cost from supplier to DCs and from DCs to customers, the sum of expected shortage cost. Equation (4.2) states that R numbers of distribution centers are to be located. The value of R is chosen by the decision maker. Equation (4.3) is the mass balance constraint. This constraint stipulates that the number of products received at the distribution centers must equal the number of products shipped to the customers. Constraint (4.4) ensures the restriction of flow of products from supplier i to distribution center j before establishment of distribution center j. Constraint (4.5) ensures that flow can`t be initiated from distribution center j to customer k until we establish distribution center j. In Equations (4.4) and (4.5), M is a sufficiently large positive number. Equation (4.6) implies demand satisfaction constraint. This constraint is commonly used in many instances in supply chain network design. A non-disrupted supply chain is obviously aimed at satisfying customer demand. Constraint (4.7) is the capacity constraint of the supplier. Constraint (4.8) expresses the capacity constraint of the distribution centers. Constraint (4.9) represents the amount of shortage in the first time period. Constraint (4.10) indicates the amount of shortage in the second time period. Constraint (4.11) decides the amount of product supplied to the distribution centers in the second time period due to disruptions of the suppliers in the first time period. As the suppliers suffer disruptions in the first time period, they can`t supply the normal flow amount (Z_{ijl}) in the second time period, rather some fraction of those amount are provided by them to the distribution centers. Constraint (4.12) imposes the integrality restrictions on binary variable. Finally, constraint (4.13) enforces the non-negativity restriction on the corresponding decision variables.

4.4 Computational Experiment

Several sets of numerical examples are used in order to demonstrate the applicability and usefulness of the proposed model. To clearly highlight the significance of considering disruptions in supply chain planning and decision making, a comparison is made between the proposed model with an emphasis on disruption risk and the basic or baseline model. A basic or baseline model is the one which is designed and operated in a condition assuming that there would be no disruptions. Most of the traditional supply chains ignore disruptions arguing those as rare events. However, the effects of disruptions seem to have catastrophic consequences on organizational existence (Knemeyer et al., 2009). In this numerical investigation, we show the effect of disruptions in terms of monetary value. We consider several sample examples having different dimensions in terms of number of distribution centers, number of customers to be served, and number of products to be provided from the suppliers and from the distribution centers. Each of the suppliers and each of the distribution centers can serve every type of products. Table 4.1 shows the range of data of the test problems. Due to the unavailability of real data, all parameters used here are assumed to be uniformly or normally distributed. Such assumption is fairly common in the supply chain literature.

We initiate our numerical experiment considering a small representative supply chain consisting of four potential DCs locations, three outside suppliers, three products and five customers located at different locations in a territory. We vary the number of potential sites for renting or establishing distribution centers, the number of customer to be served by the DCs, and the number of products to be provided in the system. We thus formulate 10 test problems (T1-T10), which are shown in Table 4.2.

Table 4.1 Range of data of the test problems

Parameters	Range of data
Investment cost for operating DCs,$	Uniform [100,300]
Product demand	Uniform [2000,3500]
Fraction of supply [Supplier to DC]	Normal [0.70,0.10]
Fraction of supply [DC to Customer]	Normal [0.80,0.10]
Transportation cost /supplier to DC,($	Uniform [0.015,0.25]
Transportation cost /DC to customer, ($)	Uniform [0.025,0.45]
Penalty cost per unit of shortage cost ($)	Uniform [0.55,1]
Space utilization rate	Uniform [2,5]
Capacity utilization rate	Uniform [2,5]
DC storage capacity	Uniform [1200,1500]
Supplier Production capacity	Uniform [2000,4000]

The number of distribution centers required for optimum solution is determined from the process of simulation. For every test instance, we have the input such as number of potential DCs, number of products, number of suppliers and number of products along with other parameters presented in Table 4.1. Under these settings, we start the experiment by putting the value of the number of DCs required to be located for optimum network configuration equals one. If the problems seem infeasible, then in the next trial we add another distribution center. In this way we find the number of distribution centers to be located for getting optimum solution. We consider 100 scenarios to test the model for each of the 10 test instances. The probability of scenario is generated from a uniformly distributed random variable defined in U[0,1] and then normalized to ensure that the sum of all probabilities is equal to one. In each scenario, we have the percentage of regular supply that is flown to downstream supply chain echelon. The values of fraction of supply are generated from a normally distributed random variable. The fraction of supply from suppliers to distribution centers is treated as normally distributed with mean 0.70 and standard deviation 0.10. The fraction of supply from distribution centers to customers is also considered as normally distributed with mean 0.80 and standard deviation 0.05 respectively. The capacity of distribution centers and suppliers are defined as uniformly distributed random variable in U[1200,1500] and U[2400,3000] respectively. The space and capacity utilization rate are also drawn as uniformly distributed random variable in U[2,5] as in the work of Sahraeian et al. (2010).

The mathematical model presented in this chapter is coded on GAMS 24.1.3 and run by CPLEX 12.5.1.0 solver on an Intel (R) Core (TM) i7-3770 Dual Processor with 24GB RAM and a 3.40GHz CPU. Table 4.3 illustrates a comparison of results between the risk-concern and the basic model in terms of the objective function value (OFV) and solution time. Moreover, some results related to the decision variables for both of the models are shown in Table 4.4. It is observed in Table 4.3 that the basic model converges quite faster than the risk concern model. In addition, in contrast to the risk concern model, the basic model demands significantly lower cost due to the absence of disruptions handling cost.

It is observed that the inclusion of disruption adds cost in the systems which are explicitly shown in Figure 4.2. This cost is modeled as penalty cost for shortages of products for disruptions. This penalty cost might be lost sales cost or the cost of purchasing the products from a competitor. Figure 4.2 reports significantly higher cost difference between the risk concern and basic model, in particular, for serving higher number of customers. Roughly, the range of the objective function values for the risk concern model approximates two to five times higher cost than the basic model. It is pointed out that the high cost difference between risk concern and basic framework depends on the extent of per unit penalty cost. Management can fix per unit penalty cost based on experience and personal judgments and can formulate different strategies and action plans in the case of disruptions.

Many firms tend to passively accept the impact of disruptions (Paul et al., 2016). The monetary comparisons between the risk concern and basic model highlight the impacts and significance of considering disruptions on today's dynamic supply chains, which are mostly vulnerable and fragile to man-made and natural disasters. It is believed that disruptions are low probability but high impact events. But, the aftermath effects of disruptions in terms of production, financial and reputational losses influence the decision makers of global supply chain to rethink and reengineer their business models considering disruptions risk. Consequently, the investigation upholds significant insights for the policy making of an enterprise that seeks to mitigate the catastrophic effects of supply chain disruptions. The analysis made in our works offers some benefits to supply chain decision making of firms. On comparing disruptions cost/disruptions recovery cost with normal operating cost, management can decide on strategies to mitigate or cope with disruptions. They can adapt to supply chain disruptions by following strategies such as emergency sourcing from a supplier or offering back-ordered sales to customers. On the other hand, they can be mentally prepared to accept the effects of disruptions and experience lost sales thereby. Table 4.4 shows some comparisons of the decision variables for the basic model and the risk concern model. Specifically, the table reports the location decision, as well as shipment policies in procuring and distributing the products at the distribution centers (DCs).

Table 4.2 Sample examples in terms of number of DCs /customers/products

Test instance	Suppliers	Potential sites for establishing DCs	Number of DCs required	Number of customers	Number of of products
T-1	3	4	1	5	3
T-2	3	6	1	8	4
T-3	3	8	1	10	5
T-4	3	10	1	12	6
T-5	3	12	2	15	8
T-6	3	15	5	20	8
T-7	3	18	12	25	10
T-8	3	20	14	30	10
T-9	3	25	17	35	10
T-10	3	40	32	50	10

Table 4.3 Objective function values and CPU time for the risk concern and basic model

Test instance	Objective function value ($)		Additional cost due to disruptions ($)	CPU time (Secs)	
	Risk concern model	Basic model (no disruptions)		Risk concern model	Basic model
T-1	27,527.372	7548.754	19,978.618	0.34	0.03
T-2	54,272.575	22,705.126	31,567.449	12.01	0.05
T-3	81,696.390	36,379.457	45,316.933	94.52	0.05
T-4	107,693.332	47,008.906	60,684.426	239.31	0.05
T-5	176,443.580	65,819.344	110,624.236	771.17	0.66
T-6	214,998.248	66,355.032	148,643.216	830.22	0.89
T-7	319,819.098	73,501.352	246,317.746	670.43	0.22
T-8	379,534.944	84,029.642	295,505.302	563.54	0.23
T-9	420,403.170	94,385.226	326,017.944	438.25	0.55
T-10	593,996.896	111,716.436	482,280.46	631.91	0.47

Table 4.4 Some results from test instance T-1

Basic model		Risk concern model	
Decision variables	Solution	Decision variables	Solution
X (location)	J_4	X (location)	J_3
Z_{ijl} (Shipped amount from suppliers)		Z_{ijl}(Shipped amount from suppliers)	
I1J4L3	14013.975	I1J3L1	13169.348
I2J4L2	13578.566	I2J3L2	12502.068
I3J4L1	11941.535	I2J3L3	14077.643
		I3J3L1	982.236
Y_{jkl} (Shipped amount from DCs)		Y_{jkl} (Shipped amount from DCs)	
J4K1L1	2375.121	J3K1L1	3300.768
J4K1L2	3003.393	J3K1L2	2342.572
J4K1L3	2653.035	J3K1L3	3405.198
J4K2L1	2539.550	J3K2L1	2963.597
J4K2L2	2527.162	J3K2L2	2317.229
J4K2L3	2197.237	J3K2L3	2043.519
J4K3L1	2225.153	J3K3L1	2763.387
J4K3L2	2883.670	J3K3L2	2698.522
J4K3L3	3264.339	J3K3L3	2970.689
J4K4L1	2346.224	J3K4L1	2532.766
J4K4L2	2998.602	J3K4L2	2186.748
J4K4L3	3163.786	J3K4L3	3192.872
J4K5L1	2455.488	J3K5L1	2591.065
J4K5L2	2165.738	J3K5L2	2956.996
J4K5L3	2753.577	J3K5L3	2465.365

Table 4.4 shows some interesting observations that are worth pointing out. We see that the solutions of the decision variables are changed when we include disruptions risks in the supply chain system we consider for our work. First we notice the selection of the distribution centers (DCs) location. It is identified that location J4 is selected in the case of basic model whereas J3 is selected while we consider disruptions risk in the model. Second, the variation of shipment decisions is also seen from Table 4.4. The reasons behind the observations might be explained from two aspects. Firstly, we consider

several scenarios in order to capture the effect of disruptions for both the supply and distribution system. Secondly, we assign cost for the amount of products shortages due to disruptions. Therefore, to minimize the effects and the associated cost of disruptions and disruptions mitigation, an alternative solution seems to have in our analysis. Thus it is concluded that inclusions of disruptions risk trigger the strategic planning and decision making of a supply chain system to hedge against unexpected supply chain disruptions. It is noted that the analysis is performed for a limited number of scenarios. Of course, the decision maker may generate infinite number of scenarios. For this, Monte Carlo approach is an effective method. To solve the large scale problem, algorithm such as Benders decomposition, or heuristics methods would be necessary. In a recent study, Garcia-Herreros et al. (2014) propose a supply chain network with facility disruptions. They apply Monte Carlo approach and Benders decomposition.

Some features of the optimization instances are shown in Table 4.5. It is seen that for larger problem size we have huge numbers of individual equations and individual variables. Table 4.5 also shows the number of binary variables used in the model.

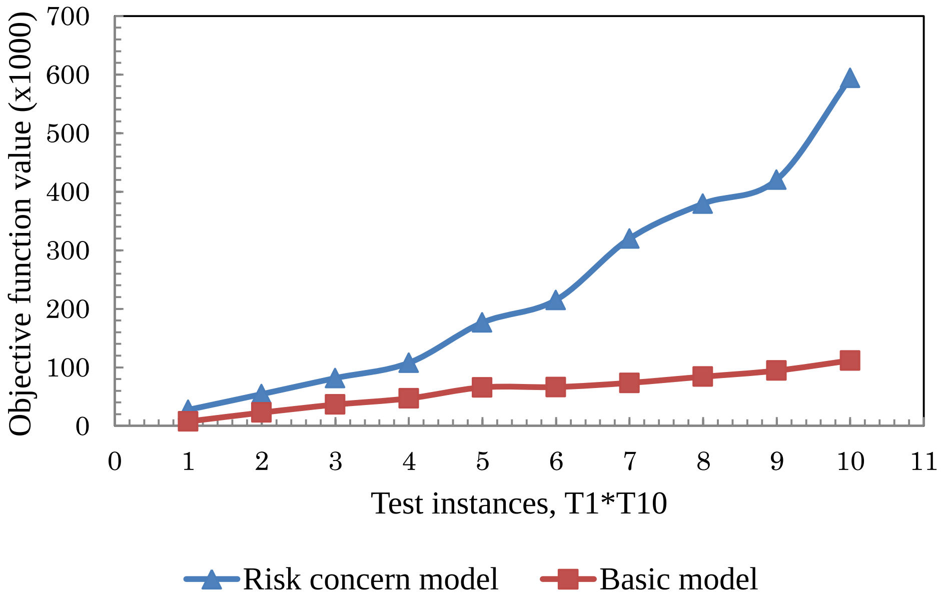

Fig. 4.2 The comparison of cost between risk concern and basic model

In this stage, we consider a separate set of experiment with a view to exploring the behavior of the model under several numbers of scenarios. Thus, for conducting the simulation experiments, we consider test instance T-5 and examine the effects of different number of scenarios on the objective function values (OFV). We begin the experiment considering ten scenarios. In each successive trial, the numbers of scenarios are increased by ten. We continue the simulation up to one hundred scenarios. The results obtained from the investigation are presented in Table 4.6. It is evident from Table 4.6 that for higher number of scenarios the CPU time increases. The reasons behind this phenomenon are that when numbers of scenarios are large, we have more decision variables and more constraints. So, it takes more time to find the optimal solution.

The values of objective function over all the scenarios are presented in Figure 4.3. For smaller number of scenarios, the values of objective functions are a bit higher than higher number of scenarios. As the sum of all scenario probabilities is one, for higher number of scenarios the expected costs tend to become lower. Therefore, values of objective function are lower for a larger number of scenarios. Thus, the model shows satisfactory performance up to this domain of experimental investigations.

Table 4.5 Some features of the optimization instances

Test instance	#of single equations	# of single variables	# of discrete variables
T-1	4,244	18,101	4
T-2	8,879	57,871	6
T-3	14,119	120,529	8
T-4	20,567	216,911	10
T-5	33,857	433,741	12
T-6	44,330	722,776	15
T-7	68,489	1,355,059	18
T-8	80,565	1,806,621	20
T-9	95,680	2,634,526	25
T-10	141,025	6,021,241	40

Table 4.6: Objective function values (OFB) and CPU time for different number of scenarios for test instance T-5

No.	#of scenarios	Objective function values (OFB),$	Solution time (Secs)
1	10	185,092.623	27.04
2	20	193,043.674	90.22
3	30	188,009.427	154.47
4	40	182,936.271	247.22
5	50	177,050.374	285.56
6	60	181,019.883	359.04
7	70	178,102.231	495.66
8	80	180,918.821	643.21
9	90	179,763.746	665.72
10	100	176,443.580	771.17

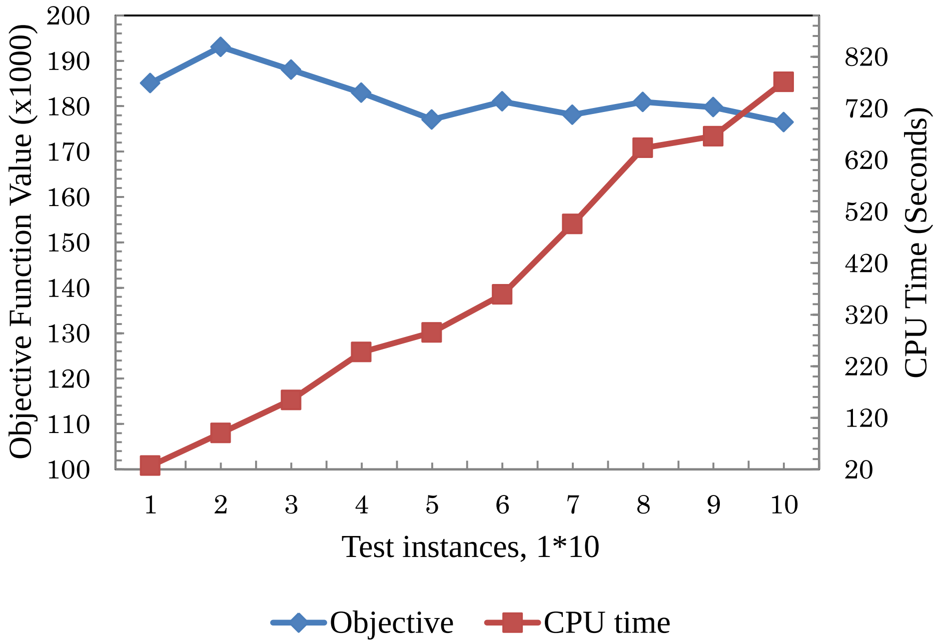

Fig. 4.3 Objective function value and CPU time for different numbers of scenarios

4.5 Conclusions

This chapter presents a mixed integer programming (MIP) model of a multi-commodity multi-stage supply chain considering disruptions risk at the location of distribution centers (DCs) and suppliers. Decisions such as the number and location of distribution centers, distribution strategies from suppliers to distribution centers (DCs), and from distribution centers (DCs) to customers are considered. Overall, our study reveals the following insights.

Firstly, it is observed that the solutions of the proposed model are highly sensitive to disruptions. The supply chain models with disruptions claim approximately two to five times higher cost than the basic model. The cost due to disruptions increases at a faster rate for higher number of customers. Secondly, the selections of location for distribution centers (DCs), as well as shipment decisions are changed in many instances while we link disruptions handling cost to the basic model. To minimize the impacts and costs associated with disruptions, the model seeks different location (DCs) and different shipment portfolio. Thus, we have considerably different distribution strategy when we include disruptions.

There are some ways by which this research can be extended in future work. Firstly, one could think of enhancing the model by including inventory management perspective under an integrated multi-period location-routing- inventory model. Secondly, it would be worth exploring to include the concept of facility hardening in the proposed supply chain disruptions management framework.

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Chapter 5

Coordinating a Supply Chain System for Production, Pricing, and Service Strategies with Disruptions

5.1 Introduction

At present, in light of the rapid advancement of information, technological innovation and globalization paradigm in the business word, companies face fierce competition to conduct business operations. Moreover, the situation gets amplified when organizations face disruptions in their network (Ali & Nakade, 2014, 2015a). Disruptions might come from natural or manmade actions. Some recent experience includes Nepal earthquake 2015, Japan earthquake and tsunami 2011, Ebola outbreak 2014 etc. In order to deal with such disruptions in an efficient and effective fashion, supply chain disruptions management are rapidly emerging as an exciting and fledging field to researchers and practitioners. Like traditional supply chain problem solving, supply chain coordination mechanisms might help in exploring supply chain disruptions issues (Qi et al., 2004).

Supply chain coordination by revenue sharing contract is all but a new concept in the literature of supply chain management (Cachon & Lariviere, 2005; Giannoccaro & Pontrandolfo, 2004; Krishnan & Winter, 2011). Recently, revenue sharing contract has gained enormous popularity in online marketplaces such as Amazon.com, Alibaba.com and eBay.com (Cao, 2014, Li et al., 2009c). Moreover, its application is widely found in organizations such as Blockbusters and its suppliers (Cachon & Lariviere, 2005), as well as in franchising companies (Wang et al., 2004). In this work, we apply revenue sharing mechanisms to coordinate a supply chain in which there are one supplier and one retailer with an emphasis on market scale and service sensitivity coefficient disruptions. The problem can be described as follows. The supplier produces the product of interest and sells to the retailer. The product is then sold on the open market by the retailer. In order to augment sales and for the growth of business, the retailer is committed to providing services to customers. Those include warranty services, maintenance and repair services, dealing with complaints, maintaining stock etc. Initially, the supplier prepares production, pricing and revenue sharing strategy as well as others resource planning based on forecasted market demand under normal supply chain circumstances. In the same way, the retailer also plans for ordering and service strategy at the time horizon in which no disruptions take place. This plan is intended to suit well for the supply chain players in a smooth supply chain environment. At the time immediately followed by disruptions, the system parameters undergo some changes. Thus, actual demand is realized after demand and service sensitivity factor disruptions. Therefore, a change in the supplier`s production and pricing plan is obvious in order to compensate for the disruptions magnitude. Similarly, the retailer also revises his pricing, service and ordering strategy when actual demand is realized. Examples of products that undergo frequent and considerable demand disruptions include fashion ware, perishable foods, Apple`s iPhone, Nintendo`s Wii video game console, tents, medicines, new magazines etc. (Huang et al., 2012; Qi et al., 2004). Thus to deal with such disruptions, changes in production, pricing, service level and revenue sharing strategies are evident for all the supply chain partners. In this situation, choosing and implementing an effective coordination mechanism might be appealing to the supply chain to minimize the negative impacts of disruptions. Such coordination policies might lead to maximization of the total supply chain profit thus benefiting the supply chain members who are connected in decentralized nature. Thus, we aim to examine the effect of demand and service sensitivity factor disruptions on the supply chain strategies and propose a coordination scheme by revenue sharing contract.

This chapter is organized as follows. Section 5.2 describes some literature on coordination by supply chain contracts with disruptions. In Section 5.3, we present the basic framework of our work. We establish the coordination policies of the supply chain system without disruptions in Section 5.4. Section 5.5 discusses the coordination issues of the supply chain system when demand and service sensitivity coefficient are disrupted. Related numerical experiments are illustrated in Section 5.6. Finally, a conclusion is drawn in Section 5.7.

5.2 Related Work

The poor supply chain performance is of prime concern at the enterprise level in view of the increased supply chain vulnerability by disruptive events for years. Our work is allied to the area of supply chain disruptions management, supply chain coordination management and supply chain contracts mechanisms. Even though the philosophies of supply chain coordination are far developed to the supply chain researchers till now, supply chain disruptions management is relatively new but interesting area in the supply chain /supply chain risk management literature. The interesting idea of disruptions management is firstly introduced by Clausen et al. (2001). They successfully apply the idea to airlines industry in solving flight and crew scheduling problems. Next, the concept of disruption management is extended to a variety of areas such as production planning (Yang et al., 2005), machine scheduling (Qi et al., 2006), project scheduling (Zhu et al., 2005), and supply chain management (Qi et al., 2004).

Supply chain contracts are promising decision making tools in order to implement coordination among different channel members operating under the decentralized environment (Giannoccaro & Pontrandolfo, 2004). Supply chain coordination is imperative to optimize supply chain performance through sharing of information and incentives (Höhn, 2010). A wide variety of contracts mechanisms are proposed in the supply chain literature. Those include wholesale price contract (Dong & Zhu, 2007; Shin & Tunca, 2010; Xu & Bisi, 2012; Kang & Yang, 2013), two-part tariff contract (Bonnet & Dubois, 2004; Wu & Chen, 2015), buyback contract (Hou et al., 2010; Xiao et al., 2010), revenue sharing contract (Cachon & Lariviere, 2005; Giannoccaro & Pontrandolfo, 2004; Palsule-Desai, 2013), quantity flexibility contract (Subramanian et al., 2006; Tsay, 1999), back-up contract (Eppen & Iyer, 1997), sales rebate contract (Chiu et al., 2011; Wong et al., 2009) and quantity discount contract (Chang & Pao, 2010; Li & Liu, 2006; Qi et al., 2004).

There are numerous studies that shed light on supply chain coordination with contracts (Cachon et al., 2003; Chiu et al., 2015; Govindan et al., 2013; Seifert et al., 2012; Xu et al., 2015). However, applying coordination to address disruptions management is relatively new in the area of supply chain management. Qi et al. (2004) pioneer the idea of solving demand disruptions issues with the application of supply chain coordination schemes. They introduce deviation cost while original production plans don’t work due to unanticipated emergent events. They use wholesale quantity discount policies to establish coordination for a supply chain composed of one supplier and one retailer. Next, Xiao et al. (2005) extend their model considering two retailers. They focus on demand promotion and demand disruptions issues together. They apply a price-subsidy rate to coordinate the supply chain. Notably, the earliest work on cost disruptions is done by Xu et al. (2006). They investigate a supplier-retailer supply chain with cost disruptions and coordinate the same using a quantity discount contract. Feng et al. (2007) study the coordination problem of one supplier-one retailer supply chain system using a revenue sharing contract. They consider both demand and price sensitivity factor disruption in the nonlinear demand function. They find that the adjusted revenue sharing contract can effectively coordinate the supply chain after a demand disruption. Xiao & Qi (2008) coordinate a supply chain having two competing retailers and one supplier with an all-unit quantity discount policy and an incremental quantity discount policy to deal with demand and cost disruption. Chen & Xiao (2009) propose linear quantity discount schedule and Groves wholesale price schedule to enable coordination of a supply chain comprising one supplier, one dominant retailer and multiple fringe retailer. Furthermore, Zhang et al. (2012) suggest ways on coordinating a one-supplier-two-retailers supply chain system with demand disruptions. They consider one and two demand disruptions scenarios and propose a feasible revenue sharing contract.

Recently, Cao et al. (2013) investigate the coordination problems of a supply chain consisted of one supplier and multiple Cournot competing retailers focusing on both demand and cost disruptions. They conclude that the revenue sharing contracts are opted to find out optimal supply chain strategies under different magnitude of disruptions. Jian et al. (2014) apply a revenue sharing contract to coordinate a supply chain that has one supplier and multiple retailers. They assume a dominant retailer in the supply chain system and consider demand and price sensitivity factor disruption. They observe that the dominant retailer and the manufacturer should adjust their original contract to react to demand disruption thus leading to earning maximum profit. Cao (2014) studies disruptions management and coordination by revenue sharing mechanisms for a dual-channel supply chain and proposes optimal pricing and production strategy.

Inspection of literature in the realm of supply chain disruptions management with coordination reflects that most of the works put an emphasis on revision of production and/or pricing policies in the event of demand disruptions. Few papers consider demand stimulating service (Ali & Nakade, 2015b; Lu et al., 2011; Tsay & Agrawal, 2000; Yan & Pei, 2009). However, at present, demand stimulating service plays a key role in doing business and to gain the competitive edge in the marketing arena. Consequently, we employ demand stimulating service in our framework. It is assumed that demand stimulating services are provided by the retailer. Thus, the primary aim of our research is devoted to examining the impact of simultaneous demand and service sensitivity factor disruptions on ordering/production, pricing, service and coordination polices for the one-supplier-one-retailer supply chain system. For this purpose, we coordinate the supply chain by applying revenue sharing contracts. Thereafter, we make a general comparison of the obtained results from revenue sharing contracts with wholesale price contracts. Thus, the results of this study pinpoint the potential application of revenue sharing contracts in making production/order strategies as well as fixing service level investment to effectively deal with supply chain disruptions issues of an organization.

For better understanding of this chapter, a definition of the different terms used here is asserted below.

Disruptions: any forms of events or series of events that hinder the regular operations of supply chain systems. Disruptions cause stopping/delaying/loss of the flows of goods /service and information of a supply chain. Large-scale disruptions sometimes partially or completely destroy supply chain facilities. The events that trigger disruptions are generally known as low probability but high impact for both local and globally operated supply chains systems. Disruptions are caused by a variety of man-made and natural causes such as terrorist attack, labor strike, political unrest, economic instability, Earthquake, Tsunami, Floods, Cyclone/Tornado, machine breakdown, accident in production/transportation/storage facilities, epidemic diseases etc. Even in geographically, politically and economically stable locations, firm are exposed to disruptions. One of the important reasons is disruptions depend on their suppliers and suppliers' suppliers (Käki et al., 2015). Thus, supply chain disruptions are function of the composition and complexity of the network.

Original contracts: The contracts which are designed and intended to work well between supply chain partners for a disruption free environment. Decision makers generally make supply chain strategy by assuming a smooth and trouble free system. However, disruptions are almost inevitable in today`s complex and geographically spanned supply chain. Therefore, supply chain strategies require adjustments to respond to disruptions.

Revised contracts: The contracts which are made in response to disruptions. When preplanned original contracts are no longer adequate to optimize system performance, the contracts are modified accordingly. Although, sometimes it needs strenuous negotiation with additional paperwork /cost for renewing contracts, those are indeed absolutely necessary for recovery from the state of supply chain breakdown and vulnerabilities.

5.3 The Basic Model

We consider a supply system that has one manufacturer and one retailer. It is assumed that market demand depends on selling price and service level of the retailer. The production plan is built at the time when the system suffers no disruptions. Generally, demand is decreasing in selling price p and increasing in demand stimulating service level s (Li et al., 2014a; Qi et al., 2004). In this work, it is thought that demand stimulating services are provided by the retailer. This assumption is similar to Ali & Nakade (2015b). Thus, we express the demand function for the retailer at the time without disruptions as follows:

$$D(p,s) = \alpha - \beta p + \gamma s. \tag{5.1}$$

Here, α is the maximum market scale for the retailer, β is the coefficient of price sensitivity, γ is the marginal effect of service on demand, D. From (5.1), it requires that $\alpha + \gamma s > \beta p$ to make the demand or order quantity to be positive. To achieve the demand stimulating service level s, a service cost is incurred to the retailer. We denote φ is the marginal cost to achieve the service level s, and then the service cost is given by $\frac{\varphi s^2}{2}$ (Lu et al., 2011; Tsay & Agrawal, 2000; Yan & Pei, 2009). Herein, the quadratic form implies diminishing returns on service providing expenditures. Using the demand function, we have the total profit for the manufacturer, the retailer and the supply chain as follows:

$$\pi_{\mathrm{m}} = (w - c)(\alpha - \beta p + \gamma s. \tag{5.2}$$

$$\pi_{\mathrm{r}} = (p - w)(\alpha - \beta p + \gamma s) - \varphi \frac{s^2}{2}. \tag{5.3}$$

$$\pi_{\mathrm{sc}} = (p - c)(\alpha - \beta p + \gamma s) - \varphi \frac{s^2}{2}. \tag{5.4}$$

First, we consider the case of a centralized supply chain system. In this system, we want to maximize profit of a whole supply chain system. It is thought that there exists a central decision maker who seeks to optimize total supply chain profit. To achieve this aim, we apply first order differentiation on Equation (5.4) as the first step, we thus obtain

$$\frac{\partial \pi_{sc}}{\partial \mathrm{p}} = 0 = \alpha - \beta p + \gamma s + \beta(c - p), \tag{5.5}$$

$\frac{\partial \pi_{sc}}{\partial \mathrm{s}} = 0 = -\varphi \mathrm{s} - \gamma(\mathrm{c} - \mathrm{p}).$ (5.6)

We now evaluate the second order condition to check for optimal solution. We find $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{p}^2} = -2\beta$, $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{p}\, \partial \mathrm{s}} = \gamma$, $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{s}\, \partial \mathrm{p}} = \gamma$, and $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{s}^2} = -\varphi$. Thus, we have the following Hessian matrix

$H = \begin{pmatrix} \frac{\partial^2 \pi_{sc}}{\partial \mathrm{p}^2} & \frac{\partial^2 \pi_{sc}}{\partial \mathrm{p}\, \partial \mathrm{s}} \\ \frac{\partial^2 \pi_{sc}}{\partial \mathrm{s}\, \partial \mathrm{p}} & \frac{\partial^2 \pi_{sc}}{\partial \mathrm{s}^2} \end{pmatrix} = \begin{pmatrix} -2\beta & \gamma \\ \gamma & -\varphi \end{pmatrix}$, as $\beta > 0, \gamma > 0, \varphi > 0$, therefore $|H| = 2\beta\varphi - \gamma^2 > 0$ and thus we obtain a negative definite Hessian. That means that π_{sc} is jointly concave in p and s. Solving (5.5) and (5.6), we get the optimal price and service level for the retailer. By substituting the values of p and s in Equation (5.4) and (5.1), we obtain the optimal profit of the chain and production quantities of the manufacturer respectively. Thus we have,

$$p_c{}^* = \frac{\alpha\varphi + (\beta\varphi - \gamma^2)c}{2\beta\varphi - \gamma^2}, s_c{}^* = \frac{(\alpha - \beta c)\gamma}{2\beta\varphi - \gamma^2},$$

$$Q_c{}^* = \frac{\beta\varphi(\alpha - \beta c)}{2\beta\varphi - \gamma^2}, \pi_{c-sc}{}^* = \frac{\varphi(\alpha - \beta c)^2}{2(2\beta\varphi - \gamma^2)}.$$

In this stage, we analyse the case of a decentralized supply chain system. In this system, each member of a supply chain wants to maximize his own profit. In a Manufacturer Stackelberg (MS) Game wherein manufacturer is the leader, the reaction function of the retailer is solved first to obtain the values of p and s. Differentiating Equation (5.3) with respect to p and s, we get the following equations:

$\frac{\partial \pi_r}{\partial \mathrm{p}} = 0 = \alpha - \beta p + \gamma s - \beta(p - w),$ (5.7)

$\frac{\partial \pi_r}{\partial \mathrm{s}} = 0 = \gamma(\mathrm{p} - \mathrm{w}) - \varphi \mathrm{s}.$ (5.8)

We now investigate the second order condition to check for optimal profit of the retailer. We find $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{p}^2} = -2\beta$, $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{p}\,\partial \mathrm{s}} = \gamma$, $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{s}\,\partial \mathrm{p}} = \gamma$, and $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{s}^2} = -\varphi$. Thus, we have the following Hessian matrix

$$H = \begin{pmatrix} \frac{\partial^2 \pi_{sc}}{\partial \mathrm{p}^2} & \frac{\partial^2 \pi_{sc}}{\partial \mathrm{p}\,\partial \mathrm{s}} \\ \frac{\partial^2 \pi_{sc}}{\partial \mathrm{s}\,\partial \mathrm{p}} & \frac{\partial^2 \pi_{sc}}{\partial \mathrm{s}^2} \end{pmatrix} = \begin{pmatrix} -2\beta & \gamma \\ \gamma & -\varphi \end{pmatrix}.$$

As $\beta > 0, \gamma > 0, \varphi > 0$, therefore $|H| = 2\beta\varphi - \gamma^2 > 0$ and thus we obtain a negative definite Hessian. That means that π_r is jointly concave in p and s. By solving Equation (5.7) and (5.8), we have the following retail price and retail service level for a given w.

$$p^* = \frac{\alpha\varphi + (\beta\varphi - \gamma^2)w}{2\beta\varphi - \gamma^2},\ s^* = \frac{(\alpha - \beta w)\gamma}{2\beta\varphi - \gamma^2}.$$

By substituting p^* and s^* into Equation (5.2), we have

$$\pi_{\mathrm{m}} = \frac{\beta\varphi(w - c)(\alpha - \beta w)}{2\beta\varphi - \gamma^2}.$$

Differentiating with respect to w and letting it equals zero provide us the following equation

$$\frac{\partial \pi_m}{\partial \mathrm{w}} = 0 = \frac{\beta\varphi(\alpha + \beta c - 2\beta w)}{2\beta\varphi - \gamma^2}.$$

Solving for w gives us the optimal wholesales price of the manufacturer, $w_d{}^* = \frac{\alpha + \beta c}{2\beta}$.

By putting the value of $w_d{}^*$ into the equations of p^* and s^*, we have the MS retail price and service level expressed by

$$p_d{}^* = \frac{c}{4} - \frac{\frac{\alpha\gamma^2}{2} - \beta\left(\frac{3\alpha\varphi}{2} - \frac{c\gamma^2}{4}\right)}{\beta(2\beta\varphi - \gamma^2)}, \text{and } s_d{}^* = \frac{\gamma(\alpha - \beta c)}{2(2\beta\varphi - \gamma^2)}.$$

Thus we have the optimal production quantities in the decentralized supply chain as follows:

$$Q_d{}^* = \frac{\beta\varphi(\alpha - \beta c)}{2(2\beta\varphi - \gamma^2)}.$$

5.4 Coordinating the Single Channel Supply Chain without Disruptions

This section is divided into two parts. In the first section, some discussions on revenue sharing contract are carried out. In the next, we turn our attention to exploring the necessary theoretical insights for coordinating the single channel decentralized supply chain system operating in a non-disrupted state.

5.4.1 A brief description on revenue sharing contract

It is obvious that supply chain performance is optimized when it is under centralized controlled. However, decentralized control would yield inefficient system performance because of two reasons (Pang, 2009). The first is the presence of information asymmetry that exists in competitive and dynamic supply chain system. The second is the effect of double marginalization phenomenon. Supply chain contracts might help to overcome such limitations of a decentralized system thus aiming to enhance the total supply chain profit so as to make it closer to the profit resulting from a centralized supply chain. Besides, it is expected that supply chain contracts would offer win-win situations to all partners in supply chain (Nalla, 2008; Nan 2013). Revenue sharing is an attractive contract to coordinate supply chain thus making it efficient even it is in decentralized setting. The contract is characterized by the two parameters (w,τ), where w is the unit wholesale price and τ is the supplier`s share of revenue generated by the retailer. In order to coordinate, it is necessary that the wholesale price (w) is lower than the unit production cost (c) in exchange for the share of the retailer (Cachon & Lariviere, 2005; Giannoccaro & Pontrandolfo, 2004; Pang, 2009). However, practically speaking, this condition is difficult to apply in real-life supply chain problems. Moreover, selling products at the fraction of production cost would increase producers` risk (Saha & Sarmah, 2015). According to some recent works, coordination is still possible in many instances when wholesale price is higher than production cost (Cao et al., 2013; Li et al., 2014b). Nowadays, the growth of online business and advertising are being revolutionized in the internet era. Thus, revenue sharing contracts are practically appealing for many firms and Websites engaging in e-commerce and e-advertising.

5.4.2 The contract mechanism under decentralized supply chain

It is well known that pursuing supply chain management objective by decentralized decision making frequently results sub-optimization in the system. To address the sub-optimization problem, supply chain coordination by contract is an efficient as well as popular tool among practitioners. However, coordination might fail if it is not able to provide additional profit to one of the supply chain partners. Thus, this section particularly emphasizes on the win-win conditions of the supply chain players in establishing coordination by revenue sharing contract.

Following the definition of the RS contract, the manufacturer`s and the retailer`s profit functions in a decentralized supply chain are given by

$$\pi_m{}^{ct} = \tau[(p^{ct} - w^{ct})(\alpha - \beta p^{ct} + \gamma s^{ct})] + w^{ct}(\alpha - \beta p^{ct} + \gamma s^{ct}) - c(\alpha - \beta p^{ct} + \gamma s^{ct}).$$

$$\pi_r{}^{ct} = (1-\tau)[(p^{ct} - w^{ct})(\alpha - \beta p^{ct} + \gamma s^{ct})] - \varphi \frac{{s^{ct}}^2}{2}.$$

Therefore, the total supply chain profit under the contract scenario is given by

$$\pi_{sc}{}^{ct} = (p^{ct} - c)(\alpha - \beta p^{ct} + \gamma s^{ct}) - \varphi \frac{{s^{ct}}^2}{2}.$$

In a Manufacturing Stackelberg (MS) game, the manufacturer and the retailer try to pursue their own objectives and the manufacturer acts as the leader. Thus, the manufacturer offers the retailer a revenue sharing contract (w^{ct}, τ) first and the retailer determines the retail price and the service level to maximize her own profit. Therefore, we find the following propositions. Propositions 5.1 and 5.2 can be derived in the similar fashion as discussed in Section 5.3.

Proposition 5.1 For a given wholesale price, the retailer sets her retail price and service level as follows.

$p^{ct} = \frac{w^{ct} + \varphi(\alpha - \beta w^{ct})}{2\beta\varphi + (\tau - 1)\gamma^2}$, and

$$s^{ct} = \frac{-\gamma(\tau-1)(\alpha-\beta w^{ct})}{2\beta\varphi+(\tau-1)\gamma^2}.$$

Proposition 5.2 For the given price and service level of the retailer, the manufacturer`s optimal responsive price is given by

$$w^{d} = \frac{-(2\alpha\beta\varphi-\alpha\gamma^2-\beta c\gamma^2+2\beta^2 c\varphi+\alpha\gamma^2\tau-2\alpha\beta\varphi\tau+\beta c\gamma^2\tau)}{2\beta\gamma^2-4\beta^2\varphi+2\beta^2\varphi\tau-2\beta\gamma^2\tau}.$$

Proposition 5.3 The following revenue sharing contract (w^{ct},τ) will coordinate the single channel supply chain. The contract satisfies

$$w^{ct} = \frac{\{\alpha\varphi+(\beta\varphi-\gamma^2)c\}\{2\beta\varphi+(\tau-1)\gamma^2\}-\alpha\varphi(2\beta\varphi-\gamma^2)}{(2\beta\varphi-\gamma^2)(1-\varphi\beta)}, \text{ and } A<\tau<B, \text{ where } A=\frac{\beta\varphi-\gamma^2}{2\beta\varphi-\gamma^2},$$

$$B = \frac{-(\beta\varphi-\gamma^2)\left(3\gamma^4+4\beta^2\varphi^2-2\beta\varphi\left(4\beta^2\varphi^2-6\beta\gamma^2\varphi+3\gamma^4\right)^{0.5}-6\beta\gamma^2\varphi\right)}{4\beta^2\gamma^2\varphi^2-6\beta\gamma^4\varphi+3\gamma^6}.$$

In general, the derived revenue sharing (RS) policy (w^{ct},τ) ensures win-win conditions for all the supply chain partners. Thus, both the supplier and the retailer achieve a higher profit in the RS policy than they obtain in the non-coordinated decentralized supply chain environment.

Proof:

In order for the coordination to be effective, the revenue sharing contracts need to satisfy the following equation (Cao, 2014; Li et al., 2014b).

$p^{ct} = P_c$; which leads to the following contract price

$$w^{ct} = \frac{\{\alpha\varphi+(\beta\varphi-\gamma^2)c\}\{2\beta\varphi+(\tau-1)\gamma^2\}-\alpha\varphi(2\beta\varphi-\gamma^2)}{(2\beta\varphi-\gamma^2)(1-\varphi\beta)}.$$

Revenue sharing contracts are attractive and acceptable to the supply chain partners when it offers more profit than without contract does (Cao, 2014; Li et al., 2014b; Luo & Yu, 2011). Thus the following conditions hold,

$\pi_m{}^{ct} > \pi_m, \quad \text{and} \quad \pi_r{}^{ct} > \pi_r.$

These conditions prove the limiting values of $\tau\,(A < \tau < B)$ for the supply chain coordination by revenue sharing contracts.

5.5 Coordinating the Single Channel Supply Chain with Disruptions

In this section, we study the coordination mechanisms of the supply chain subject to demand and service sensitivity factor disruptions. Keeping the perspective of supply chain disruptions management in thinking, we formulate a coordinated framework that might work well in normal supply chain environment as well as in post disruptions supply chain crisis. It is mentioned earlier that manufacturing, pricing, service level, ordering and marketing strategy are made on the basis of base market scale. At the time when disruption unfolds in the market, the realized demand would be different from what was forecasted at the time with a disruption free environment. Following the changes in demand, it would be routine that the manufacturing, pricing, service level, ordering and marketing strategy need to be revised. To proceed, we think that disruptions tend to change the market scale from α to $(\alpha + \Delta\alpha)$ and the service sensitivity coefficient from γ to $(\gamma + \Delta\gamma)$. In what follows $\overline{D}(p, s) = (\alpha + \Delta\alpha) - \beta\bar{p} + (\gamma + \Delta\gamma)\bar{s}$.

Thus, the supply chain profit functions of the partners become as follows

$$\bar{\pi}_m = (\bar{w} - c)(\alpha + \Delta\alpha - \beta\bar{p} + (\gamma + \Delta\gamma)\bar{s}).$$

$$\bar{\pi}_r = (\bar{p} - \bar{w})(\alpha + \Delta\alpha - \beta\bar{p} + (\gamma + \Delta\gamma)\bar{s}) - \varphi\frac{\bar{s}^2}{2}.$$

It is noted that the study of supply chain disruptions management by considering the change in market scale is usual in the literature (Cao, 2014; Qi et al., 2004; Li et al., 2014b; Ali & Nakade, 2015b). It is not surprising and unnatural to consider the change in service elasticity of demand in the context of supply chain disruptions. We list three reasons to include service sensitivity disruptions in the framework. Firstly, we hold the assumption that demand is largely dependent on the retail service along with retail price provided by retailer. Secondly, customers' psychological motivation and buying behaviour are greatly influenced by the services they are getting from the retailer in place. Thirdly, the literature lacks in considering the issue so far. Therefore, it seems interesting to readers to consider the changes in service sensitivity coefficients by disruptive events. A most recent study considering price and service level is done by Ali & Nakade (2015b). Interested readers can go through the work of Ali & Nakade (2015b) whereupon retailers` simultaneous competitions on price and service levels with disruptions are broadly outlined.

When the supply chain undergoes disruptions, the profit of the manufacturer and the retailer with the application of revenue sharing contract $(\bar{w}, \tau)$ becomes

$$\bar{\pi}_{m} = \tau[(\bar{p} - \bar{w})(\alpha + \Delta\alpha - \beta\bar{p} + (\gamma + \Delta\gamma)\bar{s})] + (\bar{w} - c)(\alpha + \Delta\alpha - \beta\bar{p} + (\gamma + \Delta\gamma)\bar{s}).$$

$$\bar{\pi}_{r} = (1 - \tau)[(\bar{p} - \bar{w})(\alpha + \Delta\alpha - \beta\bar{p} + (\gamma + \Delta\gamma)\bar{s})] - \varphi\frac{\bar{s}^2}{2}.$$

Further, the total supply chain profit under disrupted supply chain circumstances with the RS contract is given by

$$\begin{aligned}\bar{\pi}_{t} &= \bar{\pi}_{m} + \bar{\pi}_{r},\\ &= (\bar{p} - c)(\alpha + \Delta\alpha - \beta\bar{p} + (\gamma + \Delta\gamma)\bar{s}) - \varphi\frac{\bar{s}^2}{2}.\end{aligned}$$

Because the derivation of coordination mechanisms is quite similar to the methods described in Section 5.4.2 and the resulting equations are long; for simplicity, we only show the results of our investigations. We analyze the impacts of disruptions on coordination policies by numerical experiment. Detailed results of the analysis are registered in Section 5.6.

5.6 Numerical Investigations

This section is classified into two parts. First we investigate the supply chain system without disruptions. Later on, we look forward to the supply chain system suffering disruptions. In both cases, we conduct numerical experiment to support the theoretical findings. The parameters used in this experiment are provided in Table 5.1. Most of the values of the parameters are collected from the work of Ali & Nakade (2015b). Further, some values related to service sensitivity factor disruptions are assumed to aid the computational experiment process. All values are carefully chosen based on our judgement. Of course, non-negativity and integrality restrictions of the equations and conditions are ensured during picking numerical values to conduct this study.

5.6.1 Revenue sharing contracts with the baseline case (no disruptions)

We start to examine the baseline case first with wholesale price contract. The optimal solutions with wholesale price contract are illustrated in Table 5.2. The total supply chain profit and the optimal order quantity in the centralized supply chain are 139.47 and 13.79 respectively, as reported in Table 5.2. On the other hand, the values of those parameters in the decentralized supply chain are 104.60 and 6.90 respectively. In the coordinated supply chain, the retailer would be induced to increase the order size close to 13.79. By doing this, the total supply chain profit of the coordinated decentralized supply chain becomes close to 139.47. However, such full coordination is difficult to achieve in practice (Zhou et al., 2009). Even a partial coordination/near optimal coordination can improve the performance of supply chain as well as prevent the sub-optimization. Notably, the problem of sub-optimization is fairly common in decentralized decision making. Supply chain coordination is introduced among the involved players in the chain to tackle sub-optimization problem, and to boost supply chain performance. Table 5.3 demonstrates the optimal solutions of the model with revenue sharing contracts under normal supply chain circumstances. To measure the effectiveness of coordination by revenue sharing contract, we calculate supply chain efficiency by following Yao et al. (2012). For obtaining complete coordination, supply chain efficiency equals 100% (Yao et al., 2012) or close to 100% (Pang, 2009). Thus we define supply chain efficiency as follows

$$\text{Supply chain efficiency} = \frac{\text{Total supply chain profit after coordination}}{\text{Total supply chain profit in the centralized chain}}.$$

Table 5.3 reports an increase of the profit of the supply chain partners when the supply chain is coordinated by revenue sharing contracts. Suppose the manufacturer and the retailer agree on $(\mathrm{w}, \tau) = (7.98,\ 0.30)$ revenue sharing contract. In this case, our proposed coordination schemes lead to achieving around 83% of the centralized supply chain profit. It also noticed that the revenue sharing contracts are better off than wholesales contracts to the supply chain partners in the decentralized control system.

Table 5.1 The Parameters for the test problem

α	β	γ	c	$\Delta\alpha$	$\Delta\gamma$	φ
20	0.9	0.7	2	3.0,0.0,-3.0	0.05,0.0,-0.05	0.8

Table 5.2 The optimal solutions with wholesale price contract

Centralized solution				Decentralized solution					
${p_c}^*$	${s_c}^*$	${Q_c}^*$	${\pi_{c-sc}}^*$	${w_d}^*$	${p_d}^*$	${s_d}^*$	${Q_d}^*$	$({\pi_r}^*, {\pi_m}^*)$	Total supply chain profit
17.33	13.41	13.79	139.47	12.11	19.77	6.71	6.90	(34.86, 69.73)	104.60

Table 5.3 The optimal solutions with revenue sharing contract with no disruptions

p^{ct}	s^{ct}	Q^{ct}	τ	w^{ct}	${\pi_r}^{ct}$	${\pi_m}^{ct}$	Total supply chain profit
17.33	5.73	8.42	0.30	7.98	41.96	73.90	115.86

5.6.2 Revenue sharing contracts with supply chain disruptions

In order to examine the coordination mechanisms of the supply chain with disruptions, we follow the same approach which is undertaken in Section 5.1. We utilize several magnitudes of demand and service sensitivity factors disruptions. These values are shown in Table 5.4. Further, the list of supply chain efficiencies is also presented therein. It is noted that the obtained efficiencies are similar to Zhou et al. (2009) in most of the cases. These efficiencies are acquired by using our proposed revised contracts, as appeared in Table 5.4. To reformulate and redesign supply chain contracts, we herein try to maximize supply chain efficiencies. It is noted that there are many combination of (w, τ) contracts which could coordinate the supply chain and eventually some other different values of efficiencies would be obtained. However, for the sake of simplicity of analysis, we assume a value of τ to formulate our revised contracts. In the literature of supply chain management, there are three game theoretical perspectives, namely Manufacturer Stackelberg (MS), Retailer Stackelberg (RS), and Vertical Nash (VN), which are widely applied for pricing, and making contract and coordination among supply chain partners. In Manufacturer Stackelberg (MS), the manufacturer has more bargaining power than the retailer. In Retailer Stackelberg (RS), the retailer acts as a Stackelberg leader and possesses more bargaining power than the manufacturer. On the other hand, every player in the supply chain has the same bargaining power in the Vertical Nash (VN) game. In a Manufacturing Stackelberg (MS) game, the manufacturer as a leader could make proper revenue sharing contracts through the process of negotiation with the retailer. We apply the MS game in this analysis.

Table 5.5 presents the optimal solutions obtained by applying revenue sharing contracts. To establish contract policies, as an initial attempt, we find the general ranges of the revenue percentage necessary for coordination by applying Proposition 5.3. These ranges are especially important for ensuring the win-win situation of the supply chain partners. That is to say that by following the ranges, the supply chain players might obtain higher profit than decentralized non-coordinated (without the RS contracts) supply chain for most of the scenarios. We could improve total supply chain profit markedly by violating the ranges and/or fixing a wholesale price (w) lower than marginal cost of production (c). The win-win situation however is not guaranteed on those contracts. For example, when we apply $(w,\tau) = (0.12,5.12)$ for coordination, the profit of the supplier, the retailer and the supply chain become 50.37, 82.66 and 133.03 respectively. In this situation, the supply chain efficiency is equal to 95.39%. Therefore, the analysis indicates that effective coordination does not mean obtaining higher total supply chain profit or efficiency. Attaining the win-win condition bears undoubtedly importance to get contract policies to be accepted to all supply chain players. As shown in Table 5.6, the proposed contracts are more favorable to the retailer compared to the wholesale contracts. Therefore, the retailer would be convinced by these contracts. However, the contracts might not be so convincing from the manufacturer`s point of view. The manufacturer might be interested in choosing alternative contracts. Not surprising, by sacrificing higher supply chain efficiency, we can propose some other contracts as shown in Table 5.7 wherein the manufacturer gains higher profit than he gets by the contracts in Table 5.6. Table 5.7 demonstrates the percentage of increased profit with respect to wholesale price contracts under similar parameters settings. Although these contracts provide higher profit to the manufacturer and ensure win-win conditions for all, the solutions with low supply chain efficiency seem not acceptable to the supply chain coordination literature. Apart from theoretical perspective, for the real-world application, we leave the matter to the manufacture who captains in a Manufacturing Stackelberg (MS) game.

Since in the Manufacturing Stackelberg (MS) context, manufacturers get the leadership roles to offer suitable contracts, they can fix an attractive contract by negotiating with retailers. Thus, coordination by revenue sharing contracts would be in place to improve and optimize supply chain performance. Before making revenue sharing contracts, manufacturers could perform sensitivity analysis within the ranges of contracts parameters in order to have better insights into their profits due to coordination. In this paper, a sensitivity analysis is carried out on case 5 with different values of the contract parameters within the ranges given in Table 5.4. The results of the sensitivity analysis are shown in Figure 5.1. As presented in Figure 5.1, the manufacturer`s profit is increasing whereas the retailer`s profit is declining with the increase of τ. Therefore, manufacturers would make a trade-off analysis to make revenue sharing contracts practically useful for the real-world supply chain. Note that the ranges of contract parameters are valid for the specific domain of the parameters we consider in this experiment. Of course, we need different ranges under different parameters settings.

At this point of analysis, one interesting question arises in the context of disruptions management. Should the original revenue sharing contracts are still enough to establish coordination for the supply chain subject to disruptions? The numerical investigations we accomplished provide us the answers. After performing numerical experiments, it is seen that the original contracts are still applicable for case 1 only. That is, the original contracts show some level of robustness in the events when the demand and service sensitivity are increased by disruptions. To have deeper insights into this observation, we conduct a sensitivity analysis on case 1, keeping $\Delta\gamma$ constants. Results of the analysis are shown in Table 5.8. It is observed that when $\Delta\alpha = 6.0$, the original contracts fail to satisfy win-win situation. To generalize, it is stated that we could keep the original contracts as long as the increase of disruptions magnitude remains less than 30% of the base market demand provided that service sensitivity gets unchanged.

However, our observation throughout this experiment holds that it needs revised revenue sharing contracts for all other cases of disruptions magnitude to re-coordinate the supply chain. We use $\tau = 0.20$ for this analysis. We construct Figure 5.2 and Figure 5.3 to see the underlying effects of $\Delta\alpha$ and $\Delta\gamma$ on total order quantities and supply chain profits by plotting a surface graph. Figure 5.2 depicts the effect of changing $\Delta\alpha$ and $\Delta\gamma$ on the total supply chain profit. In general, when the magnitude of demand disruption is fixed, the higher (lower) the $\Delta\gamma$, the higher (lower) the total supply chain profit. Similar behavior is observed when we keep fixed the magnitude of service sensitivity factor disruption, and the demand is disrupted into both directions. Figure 5.3 displays the impacts of $\Delta\alpha$ and $\Delta\gamma$ on the optimal total order (production) quantity. As the supply chain`s total profit depends on optimal order quantity, Figure 5.3 indicates the same pattern like Figure 5.2.

Table 5.4 Revenue sharing contracts $(\bar{w}, \bar{\tau})$ with disruptions

Case	$\Delta\alpha$	$\Delta\gamma$	Ranges of $\bar{\tau}$ for coordination/win-win	Revised $(\bar{w}, \bar{\tau})$ contract	Supply chain efficiency (%)
1	3.0	0.05	$0.17 < \tau < 0.25$	(9.82,0.19)	83
2	3.0	0.00	$0.23 < \tau < 0.36$	(8.20,0.25)	87
3	3.0	-0.05	$0.28 < \tau < 0.45$	(6.98,0.30)	89
4	0.0	0.05	$0.17 < \tau < 0.25$	(8.71,0.19)	83
5	0.0	0.00	$0.23 < \tau < 0.36$	(7.98,0.30)	83
6	0.0	-0.05	$0.28 < \tau < 0.45$	(6.28,0.30)	89
7	-3.0	0.05	$0.17 < \tau < 0.25$	(7.60,0.19)	83
8	-3.0	0.00	$0.23 < \tau < 0.36$	(6.45,0.25)	87
9	-3.0	-0.05	$0.28 < \tau < 0.45$	(5.57,0.30)	89

Table 5.5 The optimal solutions in revenue sharing contracts with disruptions

Case	$\Delta\alpha$	$\Delta\gamma$	$\bar{p}$	$\bar{s}$	$\bar{Q}$	$\bar{\pi}_m$	$\bar{\pi}_r$	Total profit	Centralized profit
1	3.0	0.05	21.32	8.74	10.33	103.64	66.07	169.71	204.87
2	3.0	0.00	19.85	7.64	10.48	95.57	68.22	163.79	189.24
3	3.0	-0.05	18.67	6.65	10.52	89.27	68.39	157.66	176.68
4	0.0	0.05	18.59	7.51	8.90	76.38	48.69	125.07	150.99
5	0.0	0.00	17.33	5.73	8.42	73.90	41.96	115.86	139.46
6	0.0	-0.05	16.31	5.71	9.03	65.80	50.41	116.21	130.22
7	-3.0	0.05	15.86	6.27	7.43	53.28	33.96	87.24	105.32
8	-3.0	0.00	14.80	5.48	7.52	49.13	35.07	84.20	97.28
9	-3.0	-0.05	13.95	4.78	7.54	45.89	35.16	81.05	90.83

Table 5.6 Comparison of profit in different contracts policies for different magnitude of disruptions

Case	$\Delta\alpha$	$\Delta\gamma$	Profit of the manufacturer			Profit of the retailer		
			Wholesale contracts (w)	Original contracts (w^{ct}, τ)	Revised contracts $(\overline{w}, \overline{\tau})$	Wholesale contracts (w)	Original contracts (w^{ct}, τ)	Revised contracts $(\overline{w}, \overline{\tau})$
1	3.0	0.05	102.44	104.59	103.64	51.22	66.96	66.07
2	3.0	0.00	94.62	98.01	95.57	47.31	63.86	68.22
3	3.0	-0.05	88.34	92.54	89.27	44.17	61.23	68.39
4	0.0	0.05	75.50	78.69	76.38	37.75	43.97	48.69
5	0.0	0.00	69.73	73.90	-	34.86	41.96	-
6	0.0	-0.05	65.11	69.92	65.80	32.55	40.20	50.41
7	-3.0	0.05	52.66	55.62	53.28	26.33	25.80	33.96
8	-3.0	0.00	48.64	52.38	49.13	24.32	24.60	35.07
9	-3.0	-0.05	45.41	49.67	45.89	22.71	23.59	35.16

Table 5.7 An alternative revised contracts with higher manufacturer`s profit

Case	$\Delta\alpha$	$\Delta\gamma$	Revised contracts $(\overline{w}, \overline{\tau})$	Profit $(\overline{\pi}_m, \overline{\pi}_r)$	% profit increased for manufacturer	% Profit increased for retailer
1	3.0	0.05	(10.72,0.23)	(106.55,54.56)	4.01	6.52
2	3.0	0.00	(9.10, 0.31)	(100.96,54.93)	6.70	16.11
3	3.0	-0.05	(7.84, 0.38)	(97.01,53.50)	9.81	21.12
4	0.0	0.05	(9.30, 0.22)	(78.15,42.14)	3.51	11.63
5	0.0	0.00	(7.98, 0.30)	(73.90,41.96)	5.98	20.37
6	0.0	-0.05	(7.18, 0.40)	(72.56,37.05)	11.44	13.82
7	-3.0	0.05	(8.09,0.22)	(54.51,29.39)	3.51	11.62
8	-3.0	0.00	(7.19,0.32)	(52.23,27.25)	7.38	12.05
9	-3.0	-0.05	(6.26,0.39)	(50.25,26.66)	10.66	17.39

Table 5.8 Sensitivity analysis for case 1

Demand disruptions magnitude ($\Delta\alpha$)	Profit in wholesale contracts $(\overline{\pi}_m, \overline{\pi}_r)$	Profit in original contracts $(\overline{\pi}_m, \overline{\pi}_r)$	Profit in revised contracts $(\overline{\pi}_m, \overline{\pi}_r)$
3.0	(102.44,51.22	(104.59,66.96)	(103.64,66.07)
4.0	(112.33,56.16)	(113.86,75.70)	(114.70,69.00)
5.0	(122.68,61.34)	(123.44,84.97)	(125.26,75.35)
6.0	**(133.98,66.74)**	**(133.34, 94.77)**	**(136.29,81.99)**

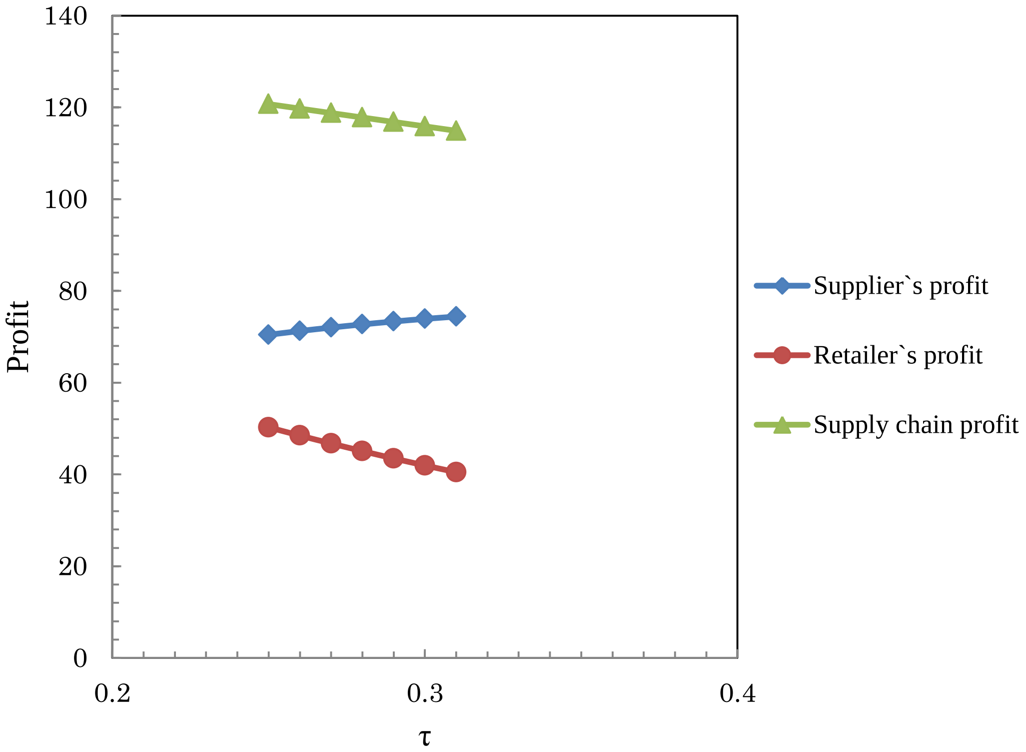

Fig. 5.1 The change of profit with respect to contract parameter τ for case 5

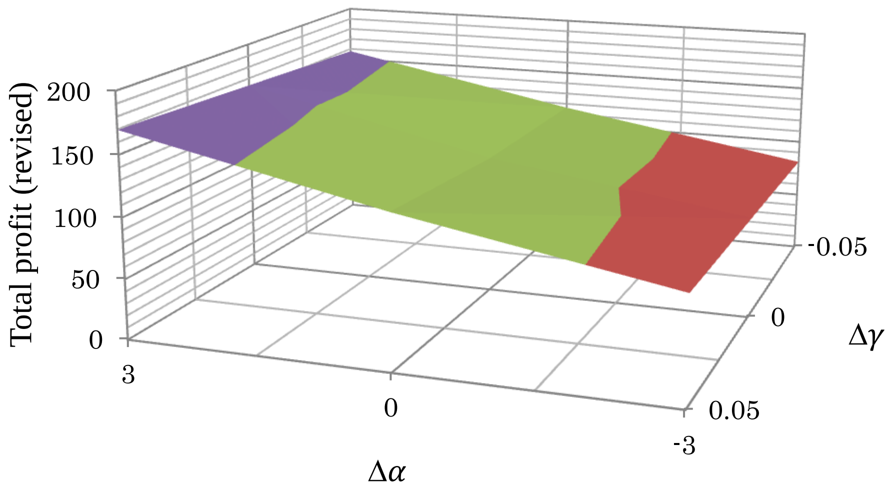

Fig. 5.2 The effect of $\Delta\alpha$ and $\Delta\gamma$ on total supply chain profit

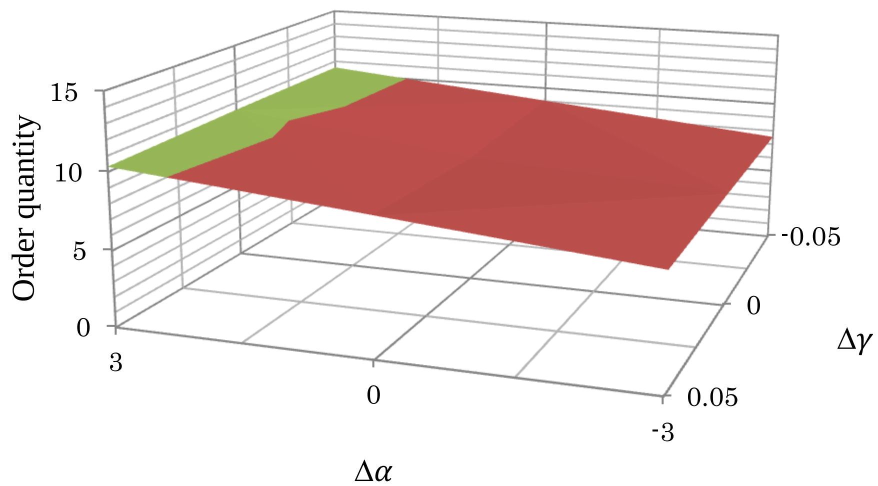

Fig. 5.3 The effect of $\Delta\alpha$ and $\Delta\gamma$ on order (production) quantity

5.7 Conclusions

In this chapter, we study the coordination policies of a supply chain system comprises one supplier and one retailer with a focus on demand and service sensitivity factor disruptions. We attempt to apply revenue sharing contracts to coordinate the supply chain operating under decentralized control. To summarize, our findings are as follows:

First, the wholesale price contract can`t coordinate and improve supply chain performance whereas the revenue sharing contract does coordinate. Even though, we report a partial coordination quantitatively achieving around 80-90% of the centralized supply chain profit, both parties involving in the chain are benefited from the results of coordination by the revenue sharing contracts. In particular, the gain of the retailer is remarkably higher in revenue sharing approaches than wholesale price contracts.

Second, our results indicate that the original revenue sharing contracts intended to work for normal supply chain environment are robust to a particular set of demand and service sensitivity disruptions. Especially when demand and service sensitivity are positively changed by disruptive events, the original contracts work up to some point. The analysis shows that for given positive service sensitivity values, original contracts are valid till market scale disruptions don’t exceed 30% of the base market demand. However, we need revised contracts for all other combinations of disruptions magnitude to optimize system performance under disruptions situations. It is important to notice that when the market scale and service sensitivity are featured by a reduction in values, the renewal of contracts are absolutely vital. With the revised contracts/policies, the supply chain gets re-coordinated accordingly.

Third, our analysis articulates that there exists a range of contract parameters for a specific domain of data in order for making the coordination satisfactory to all supply chain partners. Interestingly, the contracts could yield remarkably higher total supply chain profit beyond this range. However, win-win situations are not obtained in those situations.

The results from our work obviously show the benefit and applicability of the revenue sharing contract for real-life supply chain applications. In the future research, the proposed contract could be compared to other types of popular contracts methods such as quantity discounts, two-part tariff, or sales rebate etc. In addition, the work could be reinvestigated under multiple retailers setting.

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Chapter 6

Price and Service Competition of a Supply Chain System under Real-Time Demand Disruptions

6.1 Introduction

In order to be competitive in a market domain for conducting business successfully, managing the price of products and services offered to end customers play key roles in any supply chain system. Thus, the importance of price and service competition has increased markedly over the past few years in real life business application. Price competition attracts numerous researchers in the economics and supply chain literature. Some recent examples include the work of Mahmoodi & Eshghi (2014), Yang et al. (2014), Opornsawad et al. (2013), Wu (2012), Wang & Sun (2011), Nakade et al. (2010), Anderson & Bao (2010), Wang (2006). Despite the ever increasing importance of providing customer services in global marketing landscape, few papers consider service attribute in mathematical modeling (Jeuland & Shugan, 1983; Li et al., 2012; Lu et al., 2011; So, 2000; Tsay & Agrawal, 2004). Moreover, in most of this research, supply chain strategies are formulated by assuming disruptions free business environment. Thus, in a volatile, fragile, and haphazard business conditions existed in today's supply chain, the strategies without considering disruptions might be inappropriate. Therefore, in recent times, many researchers and practitioners are motivated to consider disruptions in building supply chain management framework in order to better hedge against the unintended risk events.

There are several types of disruptions. The two common types of disruptions are supply and demand disruptions (Ali and Nakade, 2014). Though there are several works exist in the area of supply disruptions, few attentions are given to demand disruptions (Paul et al., 2014; Qi et al., 2004; Xiao et al., 2007). It is well-known that demand is the key driver of a supply chain. Therefore, when demand disruptions occur in the chain, it significantly influences all the retailers and the suppliers existing in the chain (Huang et al., 2006; Qi et al., 2004; Wenlong et al., 2013; Xiao & Yu, 2006) and eventually the original plans need to be revised. To this end, some authors suggest coordination mechanism as a strategy to deal with demand disruptions. Cao et al. (2013) establish the coordination mechanism of a supply chain composed of one manufacturer and multiple retailers by revenue sharing contracts. Xiao et al. (2007) develop the coordination mechanism of a supply chain when retailers compete. They introduce a linear quantity discount schedule or an all-unit quantity discount schedule to mitigate demand disruptions.

Xiao & Qi (2008) follow an all-unit quantity discount or an incremental quantity discount scheme and thus establishes the coordination policy of a supply chain including one manufacturer and two competing retailers. Chen & Xiao (2009) study a supply chain consisting of one manufacturer, one dominant retailer and multiple fringe retailers. They adopt a linear quantity discount schedule and groves wholesales price schedule in order to establish coordination in the supply chain. Xiao et al. (2005) introduce price-subsidy rate and sales promotion opportunities to establish the coordination of one-manufacturer two-retailers supply chain system.

To our knowledge, none of the papers in supply chain literature formulates pricing and servicing strategy for a supply chain consisted of one supplier and multiple retailers with an emphasis on demand disruptions. Thus, this chapter makes several contributions to the supply chain literature. Firstly, most of the previous studies assume that the service would be given by manufacturer. Therefore, those studies assign the service level investment to the manufacturer. This assumption is relaxed in this study wherein the service cost is incurred to the retailer. Secondly, we mathematically derive the pricing and service strategy of the supply chain players with and without demand disruptions. Thirdly, unlike most of the supply chain literature that finds closed form analytical solutions for the price and service competition, we conduct a computational experiment to inspect the solution. This experiment could help decision makers to gain better insights into the problem.

The remainder of this chapter is structured as follows. Section 6.2 briefly describes on competing retailers` model along with its solving strategy. Section 6.3 presents and analyzes a dual channel supply chain considering disruptions risk. Section 6.4 discusses the results of the model. Finally, Section 6.5 concludes the chapter.

6.2 Competing Retailers` Model

The model of competing retailers for one supplier m and n retailer $R_{1\le i\le n}$, is shown in Figure 6.1. The supplier m incurs retailer R_i a wholesale price w_i for the product. The supplier has ample capacity to satisfy any retailer`s demand and produce the product at a constant production cost rate c_i which includes the transportation cost to retailer i. Each retailer R_i chooses his retail pricep_i and service level s_i. The demand $D_i\,(p_{i,}p_{j,}s_{i,}s_j)$ depends on the price vector $\mathrm{p} = (\mathrm{p}_1, \mathrm{p}_2, \dots, \mathrm{p}_\mathrm{n})$, $\mathrm{i} \neq \mathrm{j}$ and service level vector $\mathrm{s} = (\mathrm{s}_1, \mathrm{s}_2, \dots, \mathrm{s}_\mathrm{n})$, $\mathrm{i} \neq \mathrm{j}$. Thus, we formulate the demand function as a function of price and demand stimulating service level. Generally, the demand function for each channel is linear in self-price, cross-price, self- service and competitors` service levels but having heterogeneous parameters for all of the retailers. Further, the market demand function of a retailer is decreasing in self-price and competitors 'service level and increasing in competitors' price and self-service level. Such type of linear demand functions with more or less similar assumptions are widely reported in the economics and supply chain literature. Interested readers can go through the works of Li et al. (2014), Lu et al. (2011), Choi (1996), Raju & Roy (2000), Yue & Liu (2006), Huang et al. (2006), Hua et al. (2010), Choi (1991), Huang et al. (2009), Qi et al. (2004), Huang et al. (2012), Wenlong et al. (2013) for details. Note that it is difficult to trace multiple retailers in the same demand function. Therefore, we use the following demand function that works fine for two retailers' environment.

$$D_i\,(p_{i,}p_{j,}s_{i,}s_j) = \alpha_i - \beta_i P_i + \gamma_i P_j + \delta_i s_i - \theta_i s_{j,}\; i \neq j,\; j = 3 - i. \qquad (6.1)$$

Here, $\beta_i,\ \gamma_i$ represents the self and cross price elasticity of demand respectively; δ_i

measures the responsiveness of market demand to i^th^ retailer`s service level, θ_i is the intensity of competition in terms of service provision to their customers. $\beta_i,\ \gamma_i, \delta_i, \theta_i >$ 0 and $\beta_i >\ \gamma_i,\ \delta_i > \theta_i$ for $\forall$i. To achieve the demand stimulating service level s_i, a service cost is incurred to each retailer. Let, k is the marginal cost to achieve the service level s, then the service cost is given by $\mathrm{k}\frac{{s_i}^2}{2}$ (Lu et al., 2011; Tsay & Agrawal, 2004; Yan & Pei, 2009). Here, the quadratic form implies diminishing returns on service providing expenditures. Diminishing returns appears to be natural if the service includes a significant store level inventory component. According to Tsay & Agrawal (2000), ``under the assumption of standard inventory models, moving from, say 97% to 99% fill rate typically requires a greater incremental investment than does moving from 95% to 97%. For other concepts of service, we presume that a rational manager will always target the `lowest hanging fruit`, so that subsequent improvements are progressively more difficult``. In general, it would be more expensive to provide the next unit of service. Using the demand function and the service cost, we have the following profit functions for the retailers in a supply chain system.

$$\pi_i = (p_i - w_i)D_i - \mathrm{k}\frac{{s_i}^2}{2}, \quad \text{for } \forall \mathrm{i} \in \mathrm{n},$$

$$= (p_i - w_i)\left(\alpha_i - \beta_i P_i + \gamma_i P_j + \delta_i s_i - \theta_i s_j\right) - \mathrm{k}\frac{{s_i}^2}{2}. \quad (6.2)$$

The manufacturer profit function is given by

$$\pi_m = \sum_{i=1, i\neq j}^{n} \left((w_i - c_i)(\alpha_i - \beta_i P_i + \gamma_i P_j + \delta_i s_i - \theta_i s_j)\right). \quad (6.3)$$

Furthermore, the total profit of the supply chain will be as follows

$$\pi_{sc} = \sum_{i=1}^{n} \left((p_i - w_i)D_i - \mathrm{k}\frac{{s_i}^2}{2}\right) + \sum_{i=1}^{n}\left((w_i - c_i)D_i\right). \quad (6.4)$$

Since, it is difficult to track and solve the profit functions for multiple retailers; we concentrate on studying a supply chain comprised of two retailers. Section 6.3 derives the pricing and service strategy for such a supply chain. Following the derivation, a numerical investigation is also carried out to test the proposed approach.

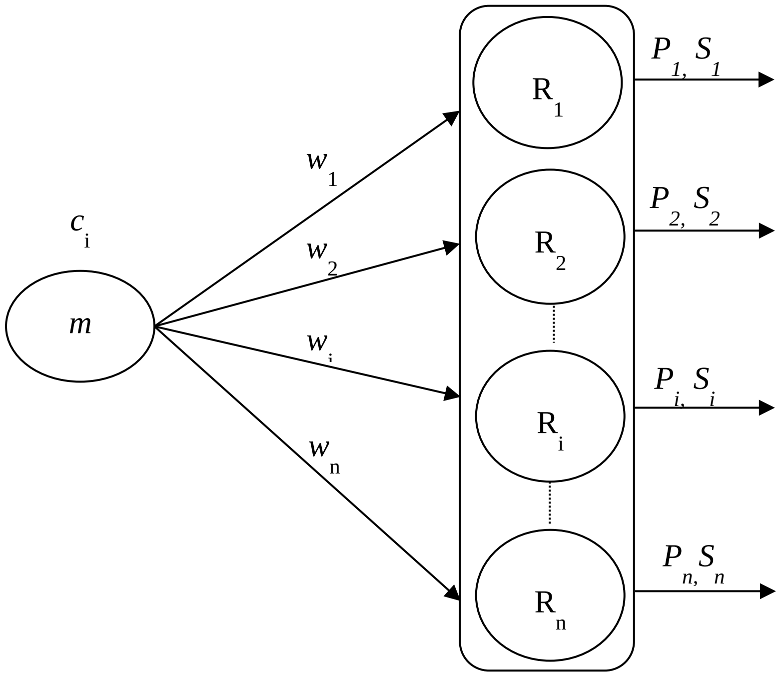

Fig. 6.1 Competing retailers' model

To examine the nature of pricing and service behavior of the manufacturer and the retailers in a supply chain system, we assume a decentralized and centralized supply chain system. For analyzing a decentralized supply chain, a game theoretical approach would be adopted. A brief description of the decentralized and centralized supply chain system is presented below:

6.2.1 Decentralized supply chain (DSC) system

In a decentralized supply chain system, each member of the supply chain seeks to maximize his own profit and there is no cooperation among the members. Over the last few decades, in the literature of supply chain management, there are three game theoretical perspectives, namely Manufacturer Stackelberg (MS), Retailer Stackelberg

(RS), and Vertical Nash (VN), which are grown more and more popular for pricing, and making contract and coordination among supply chain partners. In Manufacturer Stackelberg (MS), the manufacturer holds more bargaining power than the retailer. In Retailer Stackelberg (RS), the retailer acts as a Stackelberg leader and possesses more bargaining power than the manufacturer. On the other hand, every player in the supply chain has the same bargaining power in the Vertical Nash (VN) game. We consider Manufacturing Stackelberg (MS) game in the current study. In this system, the manufacturer is the leader and the retailer is the follower. The leader wants to maximize his profit with the information of followers' response function. The problem is solved by following the method of backward induction. The manufacturer solves the retailer`s reaction function given that the retailers has already known the wholesale price. From the given wholesale price, the retailers choose their retail price (p_i^*) and service level (s_i^*) to maximize their equilibrium profit. Further, it is assumed that all the retailers move simultaneously in the market of interest. Therefore, we have the conditions $p_i^* \in argmax_{p_i} \pi_i(p_i, p_j^* | w_i, w_j,$ and $s_i^* \in argmax_{s_i} \pi_i\left(s_i, s_j^* \middle| w_i, w_j\right)$. We thus obtain $p_i, p_{j,} s_i, s_j$ by solving these two conditions. Furthermore, from the response functions of the retailers, the manufacturer chooses their wholesale price from $w_i^* \in argmax_{w_i} \pi_m\left(w_i, w_j^* \middle| p_i, p_j, s_i, s_j\right)$.

6.2.2 Centralized supply chain (CSC) system

The profit and efficiency of a supply chain is optimized when it is under centralized control. Unlike decentralized supply chain wherein each agent of a chain wants to maximize his own profit, in a centralized supply chain setting it is assumed that there exists a central decision maker who seeks to maximize the profit of the total supply chain system. In a centralized supply chain environment, we add the profits of all the retailers and manufactures. Thus, we have $\pi_{sc} = \pi_i + \pi_m$. By differentiating and solving this equation, we can obtain the retail price and service that optimize the total supply chain profit. The following section includes a dual channel supply chain and applies the concept of centralized and decentralized supply chain settings for studying the price and service strategies, and the associated profit for the supply chain system.

6.3 A Dual Channel Supply Chain with Disruption

We consider a dual-channel supply chain composed of one manufacturer and two retailers. The manufacturer produces product and sell the product to the retail markets through the retailers as shown in Figure 6.2. The two retailers try to get more consumer access by lowering the price. Moreover, the retailers want to capture the market by providing quality service to the consumers who would like buy the product offered by the retailers. Such service may include increasing fill rate, on-time delivery, committing to after sales service etc. We assume that the retail markets undergo demand disruptions by emergent event. The demand could be increased or decreased depending on the type of product, changing customer preference, political situation, economic situation, currency fluctuation, natural and human-made disasters. Therefore, to choose effective pricing, service, as well as organizational strategy, demands disruptions carry significant theoretical and practical value to the members of a supply chain. Simply put, we are trying to examine the pricing and service policies with and without disruptions for the supply chain as displayed in Figure 6.2.

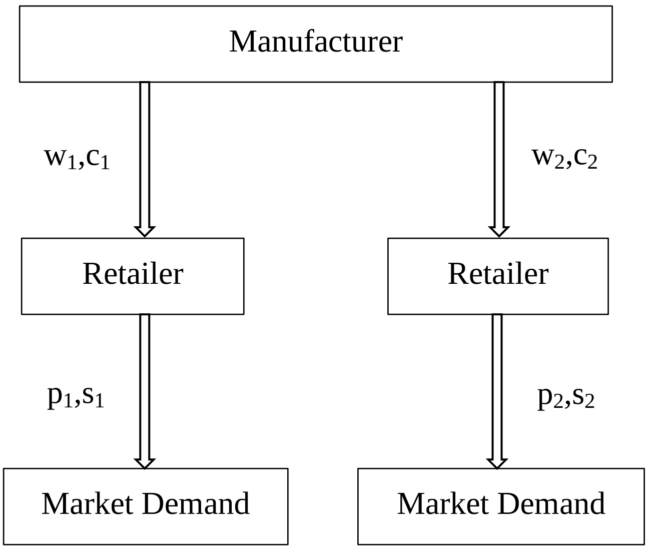

Fig. 6.2 A dual channel supply chain

The notation used here to study the dual channel supply chain is summarized below:

w_i	The unit wholesale price to retailer i
c_i	The unit production cost with transportation cost to retailer i
α_i	The market scale for retailer i
$\Delta\alpha_i$	The change of market scale due to disruptions for retailer i, $0 < \Delta\alpha_i < 0$
β_i	The coefficient of self-price elasticity for retailer i
γ_i	The degree of cross-price sensitivity between retailers i, $\beta_i > \gamma_i$
δ_i	Responsiveness of market demand to ith retailer`s service level, $\delta_i > \theta_i$
θ_i	Intensity of service competition between retailer i.
p_i	The retail price of retailer i
D_i	The market demand for retailer i
π_i	The profit of retailer i
π_m	The profit of manufacturer m
π_{sc}	The total profit of the supply chain
s_i	Customer service provided by each retailer i

6.3.1 Optimal pricing and service mechanisms under normal demand condition

We assume that the demand function for each channel is linear in self-price, self-service, cross-price and competitor`s service but having heterogeneous parameters for both of the channels in consideration. Thus, we have the following demand function

$$D_i\,(p_{i,}p_{j,}s_{i,}s_j) = \alpha_i - \beta_i P_i + \gamma_i P_j + \delta_i s_i - \theta_i s_{j,}\ i = 1{,}2 \text{ and } j = 3 - i.$$

Here, $\beta_i,\ \gamma_i, \delta_i, \theta_i > 0$ and $\beta_i >\ \gamma_i,\ \delta_i > \theta_i$, for $i = 1{,}2$ and $j = 3 - i$.

The retailer`s profit function is given by

$$\pi_i = (p_i - w_i)D_i\ - \mathrm{k}\frac{{s_i}^2}{2}, \quad i = 1{,}2,$$

$$= (p_i - w_i)\big(\alpha_i - \beta_i P_i + \gamma_i P_j + \delta_i s_i - \theta_i s_j\big) - \mathrm{k}\frac{{s_i}^2}{2}.$$

Here, to provide a service level S, the cost would be $\mathrm{k}\frac{S^2}{2}$.

In a Manufacturer Stackelberg (MS) Game wherein manufacturer gets the first mover advantage, the reaction functions of the retailers are solved first to obtain the values of p^* and s^*. Applying the first order differentiation on the above equations, we thus obtain

$$\frac{\partial \pi_i}{\partial \mathrm{p_i}} = 0 = \alpha_i - 2\beta_i P_i + \gamma_i P_j + \delta_i s_i + \beta_i w_i - s_j \theta_{i,}$$
$$\frac{\partial \pi_i}{\partial \mathrm{s_i}} = 0 = \delta_i (p_i - w_i) - k s_i.$$

We now evaluate the second order condition to check for optimal solution. We find $\frac{\partial^2 \pi_i}{\partial \mathrm{p}_i{}^2} = -2\beta_i$, $\frac{\partial^2 \pi_i}{\partial \mathrm{p_i}\, \partial \mathrm{s_i}} = \delta_i$, $\frac{\partial^2 \pi_i}{\partial \mathrm{s_i}\, \partial \mathrm{p_i}} = \delta_i$, and $\frac{\partial^2 \pi_i}{\partial \mathrm{s}_i{}^2} = -k$, as $\beta_i > 0, \delta_i > 0, k > 0$, therefore, we obtain a negative definite Hessian. Thus, the equation fulfills the condition for optimal reaction functions for retailer i. As we consider two retailers, we now have four equations to obtain the values of $P_1{}^*, P_2{}^*, s_1{}^*$ and $s_2{}^*$. We solve the equations using MATLAB R2013a. Solving the equations, the reaction functions of the retailers are as follows:

$p_i = \frac{A_1}{A_2}$ where

$$A_1 = \delta_i{}^2 \delta_j{}^2 w_i + 2\alpha_i \beta_j k^2 - \alpha_i \delta_j{}^2 k + \alpha_j \gamma_i k^2 - \alpha_j \delta_j k \theta_i + 2\beta_i \beta_j k^2 w_i - \beta_i \delta_j{}^2 k w_i - 2\beta_j \delta_i{}^2 k w_i + \beta_j \gamma_i k^2 w_j - \delta_j{}^2 \gamma_i k w_j + \beta_j \delta_j k \theta_i w_j + \delta_i \gamma_i k \theta_j w_i - \delta_i \delta_j \theta_i \theta_j w_i,$$

$$A_2 = \delta_i{}^2 \delta_j{}^2 + 4\beta_i \beta_j k^2 - 2\beta_i \delta_j{}^2 k - 2\beta_j \delta_i{}^2 k - \gamma_i \gamma_j k^2 + \delta_i \gamma_j k \theta_j + \delta_j \gamma_j k \theta_i - \delta_i \delta_j \theta_i \theta_j.$$

$\mathrm{s_i} = \frac{B_1}{B_2}$ where

$$B_1 = \delta_i \big(2\alpha_i \beta_j k - \delta_j{}^2 \gamma_i w_j - \alpha_i \delta_j{}^2 + \alpha_j \gamma_i k - \alpha_j \delta_j \theta_i + \beta_i \delta_j{}^2 w_i - 2\beta_i \beta_j k w_i + \beta_j \gamma_i k w_j + \gamma_i \gamma_j k w_i + \beta_j \delta_j \theta_i w_j - \delta_j \gamma_j \theta_i w_i\big),$$

$$B_2 = \delta_i{}^2 \delta_j{}^2 + 4\beta_i \beta_j k^2 - 2\beta_i \delta_j{}^2 k - 2\beta_j \delta_i{}^2 k - \gamma_i \gamma_j k^2 + \delta_i \gamma_i k \theta_j + \delta_j \gamma_j k \theta_i - \delta_i \delta_j \theta_i \theta_j.$$

In all these equations, $i = 1,2$ and $j = 3 - i$.

As we consider a dual channel supply chain, total profit for the manufacturer would be simply calculated by summing up the profit in each channel. Thus, the manufacturer`s profit function is given by

$$\pi_m = (w_1 - c_1)D_1 + (w_2 - c_2)D_2,$$
$$= (w_1 - c_1)(\alpha_1 - \beta_1 P_1 + \gamma_1 P_2 + \delta_1 s_1 - \theta_1 s_2)$$
$$+ (w_2 - c_2)(\alpha_2 - \beta_2 P_2 + \gamma_2 P_1 + \delta_2 s_2 - \theta_2 s_1).$$

Substituting the retailers` reaction functions p_i and s_i in the above equation and then differentiating with respect to w_i and letting those equal to zero gives the following:

$\frac{\partial \pi_m}{\partial \mathrm{w_i}} = 0 = \frac{M_1}{M_2}$ where

$$M_1 = k\big(2\beta_i{}^2\delta_j{}^2 w_i - \beta_i{}^2 c_i\,\delta_j{}^2 - \alpha_i\beta_i\delta_j{}^2 + \beta_j c_j\,\delta_i{}^2\gamma_j + 2\beta_i{}^2\beta_j c_i k - \beta_i\delta_j{}^2\gamma_i w_j - \beta_j\delta_i{}^2\gamma_j w_j - 4\beta_i{}^2\beta_j k w_i + 2\alpha_i\beta_i\beta_j k + \alpha_j\beta_i\gamma_i k - \alpha_j\beta_i\delta_j\theta_i - \beta_i\beta_j c_j\gamma_j k - \beta_i c_i\gamma_i\gamma_j k - \beta_i\beta_j c_j\delta_i\theta_j + \beta_i c_i\delta_j\gamma_j\theta_i + \beta_i\beta_j\gamma_i k w_j + \beta_i\beta_j\gamma_j k w_j + 2\beta_i\gamma_i\gamma_j k w_i + \beta_i\beta_j\delta_i\theta_j w_j + \beta_i\beta_j\delta_j\theta_i w_j - 2\beta_i\delta_j\gamma_j\theta_i w_i\big),$$

$$M_2 = \delta_i{}^2\delta_j{}^2 + 4\beta_i\beta_j k^2 - 2\beta_i\delta_j{}^2 k - 2\beta_j\delta_i{}^2 k - \gamma_i\gamma_j k^2 + \delta_i\gamma_i k\theta_j + \delta_j\gamma_j k\theta_i - \delta_i\delta_j\theta_i\theta_j.$$

In M_1 and M_2, $i = 1{,}2$ and $j = 3 - i$.

Solving for $\mathrm{w_i}$, MS wholesales price, $\mathrm{w_i}^* = \frac{Q_1}{Q_2}$. $\mathrm{w_i}^*$ is given in Appendix A.

Putting the values of $\mathrm{w_i}$ and $\mathrm{w_j}$ in the equation of $\mathrm{p_i}$ and $\mathrm{s_i}$, the MS retail prices and service levels are as follows:

MS retail price, $\mathrm{p_i}^* = \frac{\vartheta_1}{\vartheta_2}$, and MS retail service, $\mathrm{s_i}^* = \frac{\sigma_1}{\sigma_2}$.

$\mathrm{p_i}^*$ and $\mathrm{s_i}^*$ are given in Appendix B. We utilize Matlab R2013a to solve the equations. We thus far obtained π_1, π_2, & π_m. Now we consider centralized decision making.

The profit for a centralized environment is given by

$\pi_{sc} = \pi_1 + \pi_2 + \pi_m,$

$$= (p_1 - w_1)(\alpha_1 - \beta_1 P_1 + \gamma_1 P_2 + \delta_1 s_1 - \theta_1 s_2) - \mathrm{k}\frac{{s_1}^2}{2}$$

$$+ (p_2 - w_2)(\alpha_2 - \beta_2 P_2 + \gamma_2 P_1 + \delta_2 s_2 - \theta_2 s_1) - \mathrm{k}\frac{{s_2}^2}{2}$$
$$+ (w_1 - c_1)(\alpha_1 - \beta_1 P_1 + \gamma_1 P_2 + \delta_1 s_1 - \theta_1 s_2)$$
$$+ (w_2 - c_2)(\alpha_2 - \beta_2 P_2 + \gamma_2 P_1 + \delta_2 s_2 - \theta_2 s_1),$$

$=(p_1 - c_1)(\alpha_1 - \beta_1 P_1 + \gamma_1 P_2 + \delta_1 s_1 - \theta_1 s_2) + (p_2 - c_2)(\alpha_2 - \beta_2 P_2 + \gamma_2 P_1 + \delta_2 s_2 - \theta_2 s_1) - \frac{k}{2}({s_1}^2 + {s_2}^2).$

Differentiating with respect to P_i and s_i and setting them equal zero, we have the following equations.

$$\frac{\partial \pi_{sc}}{\partial \mathrm{p_i}} = 0 = \alpha_i + \beta_i c_i - 2\beta_i P_i + \gamma_i P_j + \delta_i s_i - s_j\theta_i - \gamma_j(c_j - p_j),$$
$$\frac{\partial \pi_{sc}}{\partial \mathrm{s_i}} = 0 = \theta_j(c_j - p_j) - \delta_i(c_i - p_i) - ks_i.$$

We now evaluate the second order condition to check for optimal solution. We find $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{p}_i{}^2} = -2\beta_i$, $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{p_i}\,\partial \mathrm{s_i}} = \delta_i$, $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{s_i}\,\partial \mathrm{p_i}} = \delta_i$, and $\frac{\partial^2 \pi_{sc}}{\partial \mathrm{s}_i{}^2} = -k$, as $\beta_i > 0, \delta_i > 0, k > 0$, therefore, we obtain a negative definite Hessian. Thus, the equation fulfills the condition for obtaining maximum profit in a centralized supply chain.

Solving the equations, we have the optimal retail prices, service level as follows:

Optimal retail price, ${p_i}^* = \frac{A}{B}$ for $i = 1{,}2$ and $j = 3 - i$.

Here,

$$\mathrm{A} = (2\beta_j c_i k - c_i{\theta_j}^2){\theta_i}^2 + (\alpha_j\delta_j k - \beta_j c_j \delta_j k - 2c_i\delta_j\gamma_i k - c_i\delta_j\gamma_j k + 2c_i\,\delta_i\delta_j\theta_j)\theta_i$$
$$+ c_i{\gamma_i}^2k^2 - c_i{\delta_i}^2{\delta_j}^2 - 2\alpha_i\beta_j k^2 + \alpha_i{\delta_j}^2k - \alpha_j\gamma_i k^2 - \alpha_j\gamma_j k^2 + \alpha_i k{\theta_j}^2$$
$$+ \alpha_j\delta_i k\theta_j - 2\beta_i\beta_j c_i k^2 + \beta_i c_i{\delta_j}^2k + 2\beta_j c_i{\delta_i}^2k - \beta_j c_j\gamma_i k^2 + \beta_j c_j\gamma_j k^2$$
$$+ c_j{\delta_j}^2\gamma_i k + c_i\,\gamma_i\gamma_j k^2 + \beta_i c_i\,k{\theta_j}^2 + c_j\gamma_i k{\theta_j}^2 - \beta_j c_j\delta_i k\theta_j - 2c_i\delta_i\gamma_i k\theta_j$$
$$- c_i\delta_i\gamma_j k\theta_j,$$

and,

$$B = \left(-\theta_j{}^2 + 2\beta_j k\right)\theta_i{}^2 + \left(2\delta_i\delta_j\theta_j - 2\delta_j\gamma_j k - 2\delta_j\gamma_i k\right)\theta_i - \delta_i{}^2\delta_j{}^2 + 2\beta_j\delta_i{}^2 k - 2\delta_i\gamma_i k\theta_j - 2\delta_i\gamma_j k\theta_j + 2\beta_i\delta_j{}^2 k + \gamma_i{}^2\, k^2 + 2\gamma_i\gamma_j k^2 + \gamma_j{}^2 k^2 - 4\beta_i\beta_j k^2 + 2\beta_i k\theta_j{}^2.$$

Optimal service level, $s_i{}^* = \frac{Z}{Y}$ for $i = 1,2$ and $j = 3 - i$.

$$Z = -(\theta_j\left(\alpha_j\theta_i{}^2 + \alpha_i\delta_j\theta_i - \beta_j c_j\theta_i{}^2 + c_i\gamma_j\theta_i{}^2 + c_j\delta_j\gamma_i\theta_i - \beta_i c_i\delta_j\theta_i\right) - \delta_i\left(\alpha_i\delta_j{}^2 + \alpha_j\delta_j\theta_i - \beta_i c_i\delta_j{}^2 + c_j\delta_j{}^2\gamma_i + c_i\delta_j\gamma_j\theta_i - \beta_j c_j\delta_j\theta_i\right) + k(\delta_i\left(2\alpha_i\beta_j + \alpha_j\gamma_i + \alpha_j\gamma_j + c_i\gamma_j{}^2 - 2\beta_i\beta_j c_i + \beta_j c_j\gamma_i - \beta_j c_j\gamma_j + c_i\gamma_i\gamma_j\right) - \theta_j\left(2\alpha_j\beta_i + \alpha_i\gamma_i + \alpha_i\gamma_j + c_j\gamma_i{}^2 - 2\beta_i\beta_j c_j - \beta_i c_i\gamma_i + \beta_i c_i\gamma_j + c_j\gamma_i\gamma_j)\right)\Big),$$

$$Y = -\delta_i{}^2\delta_j{}^2 + 2\beta_j\delta_i{}^2 k + 2\delta_i\delta_j\theta_i\theta_j - 2\delta_i\gamma_i k\theta_j - 2\delta_i\gamma_j k\theta_j + 2\beta_i\delta_j{}^2 k - 2\delta_j\gamma_i k\theta_i - 2\delta_j\gamma_j k\theta_i + \gamma_i{}^2 k^2 + 2\gamma_i\gamma_j k^2 + \gamma_j{}^2 k^2 - 4\beta_i\beta_j k^2 + 2\beta_j k\theta_i{}^2 + 2\beta_i k\theta_j{}^2 - \theta_i{}^2\theta_j{}^2.$$

In the next section, we investigate pricing and service strategy in response to real-time demand disruptions.

6.3.2 Optimal pricing and service mechanisms under demand disruptions

In this stage, we formulate pricing and service strategies for the two retailers while emphasizing on demand disruptions. Thus, it is assumed that when a disruption happens in the retail market it stimulates changes in market scale α_i for $i = 1,2$. Actually, α_i indicates the maximum possible demand that is anticipated on the basis of demand forecasting techniques. Management determines α_i and plans accordingly. However, this plans needs modification based on real-time demand fluctuations. Because, forecasting values always differ from real-time demand observations. In this study, the effect of disruptions is captured by $\Delta\alpha_i$. Thus, the new market scale in the event of disruptions would be $\alpha_i = \alpha_i + \Delta\alpha_i$. The change of demand $(\Delta\alpha_i)$ can be characterized as deterministic (Paul et al., 2014; Wenlong et al., 2013; Xiao & Qi, 2008) or stochastic

(Xiao & Choi, 2010) depending on decision maker`s preferences. It is important to note that after observing demand in real-time, the wholesales/retail price and service levels are $\overline{w}_i$, $\overline{p}_{i,}$ and $\overline{s}_i$ respectively.

The demand functions after disruptions thus become,

$$\overline{D}_1 = \Big((\alpha_1 + \Delta\alpha_1) - \beta_1\overline{p}_1 + \gamma_1\overline{p}_2 + \delta_1\overline{s}_1 - \theta_1\overline{s}_2\Big),$$
$$\overline{D}_2 = \Big((\alpha_2 + \Delta\alpha_2) - \beta_2\overline{p}_2 + \gamma_2\overline{p}_1 + \delta_2\overline{s}_2 - \theta_2\overline{s}_1\Big).$$

In this stage, we derive the expression for pricing and service mechanisms for both the decentralized and centralized supply chain system under real-time demand disruptions.

6.3.2.1 Demand disruptions in a decentralized supply chain

For a decentralized supply chain, every member of the supply chain wants to maximize his own profit. Here, no cooperation exists among the players in a supply chain system. Considering real-time demand disruptions, the profit of the manufacturer and the retailers would be as follows:

$$\overline{\pi}_m = \textstyle\sum_{i=1,j=3-i}^{2}[(\overline{w}_i - c_i)\overline{D}_i], \qquad i = 1,2 \text{ and } j = 3-i,$$
$$= (\overline{\mathrm{w}}_1 - c_1)\Big((\alpha_2 + \Delta\alpha_2) - \beta_2\overline{p}_2 + \gamma_2\overline{p}_1 + \delta_2\overline{s}_2 - \theta_2\overline{s}_1\Big)$$
$$+ (\overline{w}_2 - c_2)\Big((\alpha_2 + \Delta\alpha_2) - \beta_2\overline{p}_2 + \gamma_2\overline{p}_1 + \delta_2\overline{s}_2 - \theta_2\overline{s}_1\Big),$$

and

$$\overline{\pi}_i = \left(\overline{p}_i - \overline{w}_i\right)\Big((\alpha_i + \Delta\alpha_i) - \beta_i\overline{P}_i + \gamma_i\overline{P}_j + \delta_i\overline{s}_i - \theta_i\overline{s}_j\Big) - \mathrm{k}\frac{\overline{s}_i^{\,2}}{2}.$$

We again apply the Manufacturing Stackelberg (MS) game theoretical approach to determining the retail price, retail service, and wholesale price. The equations are given in Appendix C.

6.3.2.2 Demand disruptions in a centralized supply chain

In a centralized supply chain, we are interested to maximize the total profit of the whole supply chain. The literature of supply chain notifies that supply chain can perform better under centralized decision making. It is observed that solving the profit function under centralized setting is rather simple and straightforward unlike the Manufacturing Stackelberg (MS)/Retailer Stackelberg (RS)/Vertical Nash (VN) game theoretical approach.

Considering demand disruptions, we have the following profit function:

$$\begin{aligned}
\bar{\pi}_{sc} &= \textstyle\sum_{i=1,j=3-i}^{2}\left[\left(\bar{p}_i - c_i\right)\bar{D}_i\right] - \frac{k}{2}\sum_{i=1}^{2}\bar{s}_i^{\,2},\\
&= \left(\bar{p}_1 - c_1\right)\left((\alpha_1 + \Delta\alpha_1) - \beta_1\bar{p}_1 + \gamma_1\bar{p}_2 + \delta_1\bar{s}_1 - \theta_1\bar{s}_2\right)\\
&\qquad + \left(\bar{p}_2 - c_2\right)\left((\alpha_2 + \Delta\alpha_2) - \beta_2\bar{p}_2 + \gamma_2\bar{p}_1 + \delta_2\bar{s}_2 - \theta_2\bar{s}_1\right)\\
&\qquad - \frac{k}{2}\left(\bar{s}_1^{\,2} + \bar{s}_2^{\,2}\right).
\end{aligned}$$

Following the similar procedure described in Section 6.3, we obtain the optimal retail price and service under demand disruptions as follows:

Optimal price, $\bar{\mathrm{p}}_{\mathrm{i}}^{\,*} = \frac{\rho_1}{\rho_2}$ where, i=1,2 ; j=3-i and

$$\begin{aligned}
\rho_1 = {} & \left(2\beta_j c_i k - c_i\theta_j^2\right)\theta_i^2\\
& + \left(\alpha_j\delta_j k + \delta_j\Delta\alpha_j k - \beta_j c_j\delta_j k - 2c_i\delta_j\gamma_i k - c_i\delta_j\gamma_j k + 2c_i\delta_i\delta_j\theta_j\right)\theta_i\\
& + \Delta\alpha_i k\theta_j^2 - c_i\delta_i^2\delta_j^2 + c_i\gamma_i^2 k^2 - 2\alpha_i\beta_j k^2 + \alpha_i\delta_j^2 k - 2\beta_j\Delta\alpha_i k^2\\
& + \delta_j^2\Delta\alpha_i k - \alpha_j\gamma_i k^2 - \alpha_j\gamma_j k^2 - \Delta\alpha_j\gamma_i k^2 - \Delta\alpha_j\gamma_j k^2 + \alpha_i k\theta_j^2 + \alpha_j\delta_i k\theta_j\\
& + \delta_i\nabla\alpha_j k\theta_j - 2\beta_i\beta_j c_i k^2 + \beta_i c_i\delta_j^2 k + 2\beta_j c_i\delta_i^2 k - \beta_j c_j\gamma_i k^2 + \beta_j c_j\gamma_j k^2\\
& + c_i\gamma_i\gamma_j k^2 + \beta_i c_i k\theta_j^2 + c_j\gamma_i k\theta_j^2 - \beta_j c_j\delta_i k\theta_j - 2c_i\delta_i\gamma_i k\theta_j - c_i\delta_i\gamma_j k\theta_j,
\end{aligned}$$

$$\begin{aligned}
\rho_2 = {} & \left(-\theta_j^{\,2} + 2\beta_j k\right)\theta_i^{\,2} + \left(2\delta_i\delta_j\theta_j - 2\delta_j\gamma_j k - 2\delta_j\gamma_i k\right)\theta_i - \delta_i^{\,2}\delta_j^{\,2} + 2\beta_j\delta_i^{\,2}k\\
& - 2\delta_i\gamma_i k\theta_j - 2\delta_i\gamma_j k\theta_j + 2\beta_i\delta_j^{\,2}k + \gamma_i^{\,2}k^2 + 2\gamma_i\gamma_j k^2 + \gamma_j^{\,2}k^2\\
& - 4\beta_i\beta_j k^2 + 2\beta_i k\theta_j^{\,2}.
\end{aligned}$$

Optimal service level, $\bar{s}_i^{\,*} = \frac{\epsilon_1}{\epsilon_2}$ where

$$\begin{aligned}\epsilon_1 = -(\theta_j\big(&\alpha_j\theta_i^2 + \Delta\alpha_j\theta_i^2 + \alpha_i\Delta_j\theta_i + \delta_j\Delta\alpha_i\theta_i - \beta_j c_j\theta_i^2 + c_i\gamma_j\theta_i^2 + c_j\delta_j\gamma_i\theta_i \\ &- \beta_i c_i\delta_j\theta_i\big) \\ &- \delta_i\big(\alpha_i\delta_j^2 + \delta_j^2\Delta\alpha_i + \alpha_j\delta_j\theta_i + \delta_j\Delta\alpha_j\theta_i - \beta_i c_i\delta_j^2 + c_j\delta_j^2\gamma_i + c_i\delta_j\gamma_j\theta_i \\ &- \beta_j c_j\delta_j\theta_i\big) \\ &+ k\Big(\delta_i\big(2\alpha_i\beta_j + 2\beta_j\Delta\alpha_i + \alpha_j\gamma_i + \alpha_j\gamma_j + \Delta\alpha_j\gamma_i + \Delta\alpha_j\gamma_j + c_i\gamma_j^2 \\ &- 2\beta_i\beta_j c_i + \beta_j c_j\gamma_i - \beta_j c_j\gamma_j + c_i\gamma_i\gamma_j\big) \\ &- \theta_j\big(2\alpha_j\beta_i + 2\beta_i\Delta\alpha_j + \alpha_i\gamma_i + \alpha_i\gamma_j + \Delta\alpha_i\gamma_i + \Delta\alpha_i\gamma_j + c_j\gamma_i^2 - 2\beta_i\beta_j c_j \\ &- \beta_i c_i\gamma_i + \beta_i c_i\gamma_j + c_j\gamma_i\gamma_j)\big)\Big),\end{aligned}$$

$$\begin{aligned}\epsilon_2 = -\delta_i^2\delta_j^2 &+ 2\beta_j\delta_i^2 k + 2\delta_i\delta_j\theta_i\theta_j - 2\delta_i\gamma_i k\theta_j - 2\delta_i\gamma_j k\theta_j + 2\beta_i\delta_j^2 k - 2\delta_j\gamma_i k\theta_i \\ &- 2\delta_j\gamma_j k\theta_i + \gamma_i^2 k^2 + 2\gamma_i\gamma_j k^2 + \gamma_j^2 k^2 - 4\beta_i\beta_j k^2 + 2\beta_j k\theta_i^2 + 2\beta_i k\theta_j^2 \\ &- \theta_i^2\theta_j^2.\end{aligned}$$

Although it is true that a centralized supply chain system gives optimal profit and performance as compared to decentralized supply chain; however, from practical point of view, it is difficult to establish centralized control in a supply chain having many partners. In the next section, we numerically investigate the theories developed so far. We also investigate cost disruptions along with demand disruptions.

6.4 Analytical Results

In this section, we first numerically compute wholesale price, retail price, retail service level and optimal profit for both centralized and decentralized supply chain with and without demand disruptions. We use deterministic demand disruptions value in a single period setting in our work. In addition, we apply single disruption in the time period. To make the analysis simple, we assume some values of the parameters to be equal. The values of those parameters are $c_1 = c_2 = 2$, $\beta_1 = \beta_2 = 1$, $\gamma_1 = \gamma_2 = 0.6$, $\delta_1 = \delta_2 =$

1, $\theta_1 = \theta_2 = 0.7$, $\alpha_1 = \alpha_2 = 20$, We assume service cost coefficient $k = 0.8$, and demand disruptions scenario $\Delta\alpha_1 = \Delta\alpha_2 = \pm 3$. Table 6.1 shows the values of the decision variables and profit under several supply chain attributes. It is noted that, under such type of symmetry conditions the decision variables become equal (Opornsawad et al., 2013) i.e., $\mathrm{w}_1 = w_2, \mathrm{p}_1 = \mathrm{p}_2$ and $\mathrm{s}_1 = \mathrm{s}_2$. Therefore, we mention the wholesale price, retail prices, and retail services only once in Table 6.1. It is also worth mentioning that the solutions obtained are the Nash equilibrium wholesale/retail prices and retail services in the decentralized supply chain architectures under the Manufacturing Stackelberg (MS) game. On the contrary, for the centralized supply chain the retail prices and retail services imply optimal prices and services that optimize the total profit of the supply chain. Notice that (i) and (m) denote retailer`s and manufacturer`s profit respectively for the decentralized supply chain setting..

Table 6.1 presents the optimal profit under normal and disrupted demand scenarios for both centralized and decentralized supply chain strategy. It is observed that the supply chain maximizes its profit when the players are engaged in a centralized environment with increased demand scenario, whereas a significant drop of profit seems to appear in decreased demand state for both of the supply chain features. It is important to note that wholesale/retail prices and retail services and other resource requirements are determined with an assumption of no disruptions ($\Delta\alpha_i = 0$). Therefore, this plan needs to be modified in the presence of disruptions. Supply chain decision makers could revise the price strategy based on the magnitude of demand disruptions. In so doing, they could optimize the profit as well as resource of firms.

In Section 6.3.2, we derive the expressions for price and service mechanisms under demand disruptions. Similar fashion can be adopted to analytically derive the formulae while considering demand and cost disruptions together. However, to avoid the lengthy equations under such cases, we limit our analysis to numerically investigate the effect of cost disruptions. In our previous investigation, we start the experiment considering $\mathrm{c}_1 = c_2 = 2$. Now, we assume that revised cost for retailer i is $\mathrm{c}_{\mathrm{ri}} = \mathrm{c}_{\mathrm{i}} + \Delta c_i$, where, c_{i} equals the cost of retailer i in pre-disruptions supply chain strategy. For the simplicity of analysis, we consider $\Delta c_i = \Delta c_j$. From Table 6.2 and 6.3, it can be generalized that the larger the Δα, the higher the wholesale/ retail price, retail service and corresponding profit. It can also be seen that the larger the Δc, the higher the wholesale and retail price. Note that the increase of cost results in the decrease of service level and the profit of the individual members of the supply chain.

Table 6.1 The demand disruptions and the centralized and decentralized solution

Supply chain attributes	$\Delta\alpha_i$ (i=1,2)	Wholesale price	Retail price	Retail service	Optimal profit
Centralized supply chain	3.0	-	34.29	12.11	716.86
	0.0	-	29.93	10.47	536.20
	-3.0	-	25.56	8.84	381.73
Decentralized supply chain	3.0	29.75	40.58	13.54	43.98 (i)
					601.02 (m)
	0.0	26.00	35.37	11.71	32.89 (i)
					449.56 (m)
	-3.0	22.25	30.15	9.88	23.42 (i)
					320.05 (m)

Table 6.2 The demand and cost disruptions and the centralized solution

Test case	$\Delta\alpha_i$ (i=1,2)	Δc	Retail price	Retail service	Optimal profit
1	3.0	0.5	34.50	12.00	704.00
2	3.0	0.0	34.29	12.11	716.86
3	3.0	-0.5	34.08	12.22	729.83
4	0.0	0.5	30.14	10.36	525.09
5	0.0	0.0	29.93	10.47	536.20
6	0.0	-0.5	29.72	10.58	547.43
7	-3.0	0.5	25.77	8.73	372.36
8	-3.0	0.0	25.56	8.84	381.73
9	-3.0	-0.5	25.35	8.95	391.21

Table 6.3 The demand and cost disruptions and the decentralized solution

Test case	$\Delta\alpha_i$ (i=1,2)	Δc	Wholesale price	Retail price	Retail service	Optimal profit
1	3.0	0.5	30.00	40.73	13.41	43.19 (i)
						590.24 (m)
2	3.0	0.0	29.75	40.58	13.54	43.98 (i)
						601.02 (m)
3	3.0	-0.5	29.50	40.43	13.66	44.77 (i)
						611.90 (m)
4	0.0	0.5	26.25	35.52	11.59	32.21 (i)
						440.24 (m)
5	0.0	0.0	26.00	35.37	11.71	32.89 (i)
						449.56 (m)
6	0.0	-0.5	25.75	35.21	11.83	33.58 (i)
						458.98 (m)
7	-3.0	0.5	22.50	30.30	9.76	22.84 (i)
						312.20 (m)
8	-3.0	0.0	22.25	30.15	9.88	23.42 (i)
						320.05 (m)
9	-3.0	-0.5	22.00	30.00	10.00	24.00 (i)

There are many parameters used in the model. However, we are interested to explore the effect of price competition intensity and market responsiveness on supply chain decisions under both normal and disrupted demand scenario. First, we vary price competition intensity γ from 0.1 to 0.8 keeping all other things constant. In this investigation, we assume that the realized demand disruption value is positive i.e. $\Delta\alpha_i > 0$. We use $\Delta\alpha_1 = \Delta\alpha_2 = 3$ in this analysis. The characteristics of the concerned variables are plotted in Figure 6.3, 6.4 and 6.5. From Figure 6.3 it is seen that the profit, retail prices, and retail services tend to increases when the intensity of price competition increases. However, the retail price and total profit are more sensitive to the intensity of price competition than the retail services do. In fact, when the intensity of price competition increases, the demand for a retailer increases. Thus, we have an increasing trend with the increase of γ. Therefore, the increased demand scenario lead to the significant increase of profit and retail price than the non-disrupted demand condition. Similar price and service patterns are obtained for a decentralized supply chain in Figure 6.4. However, as shown in Figure 6.5, the profit for the manufacturer is much more sensitive to price competition factor γ than the retailers are.

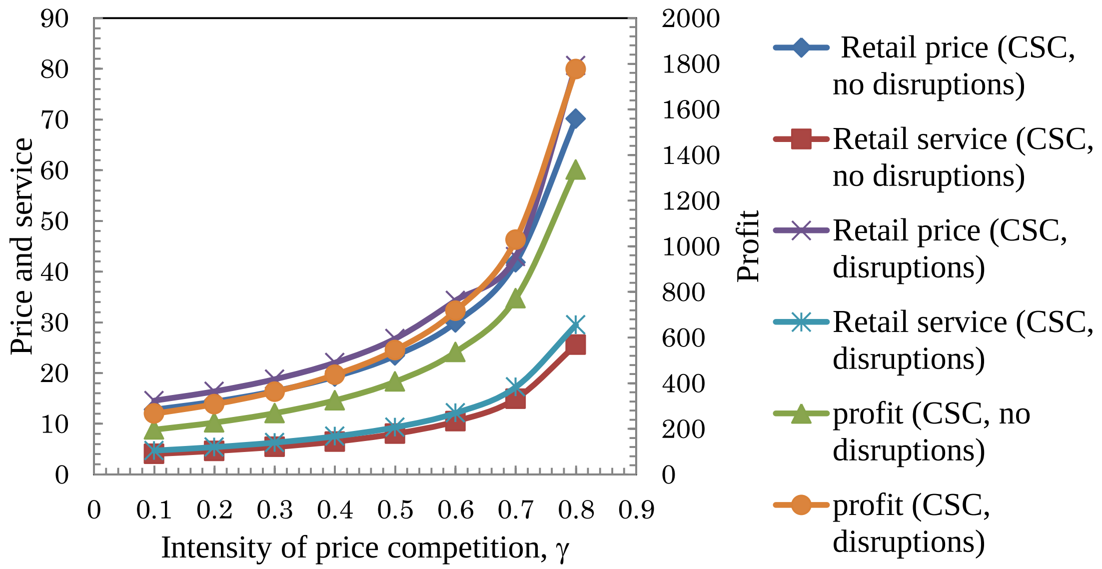

Fig. 6.3 The change of retail price, retail service and total profit when γ increases in the centralized supply chain

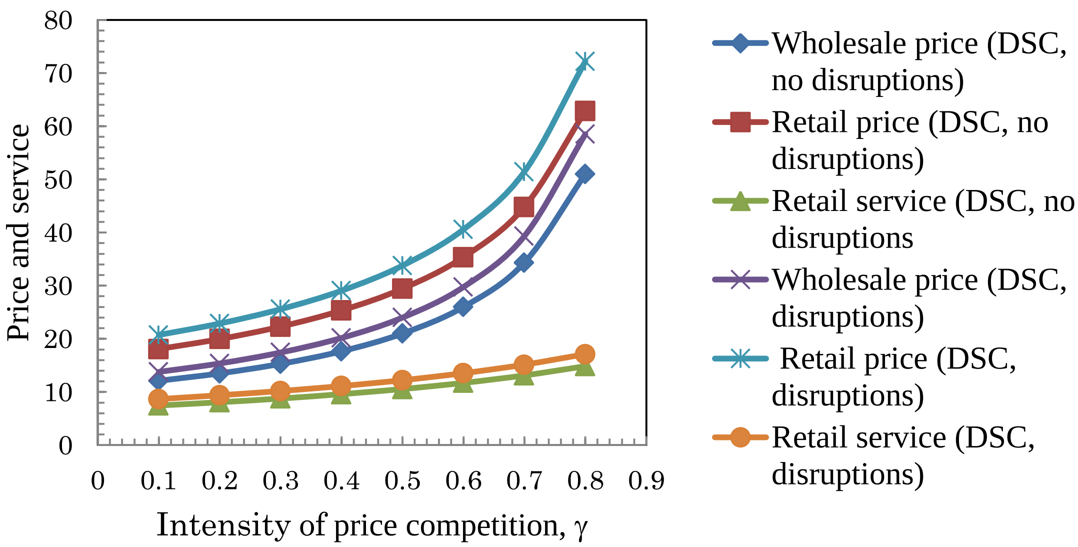

Fig. 6.4 The change of wholesale price, retail price and retail service when γ increases in the decentralized supply chain

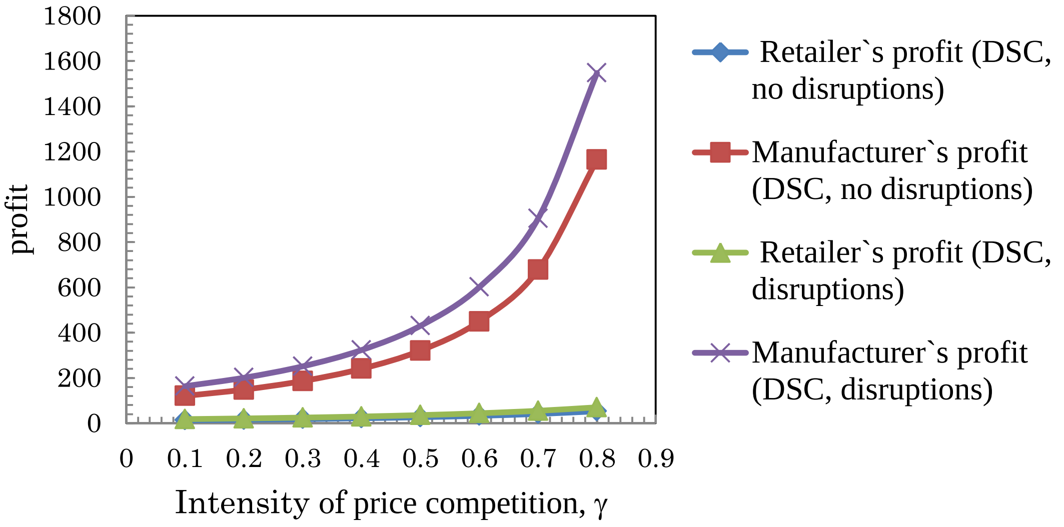

Fig. 6.5 The change of supply chain agent`s profit when γ increases in the decentralized supply chain

We vary the responsiveness of market demand (δ) from 1.00 to 1.18 as shown in Figure 6.6, 6.7 and 6.8 while keeping all other parameters fixed.

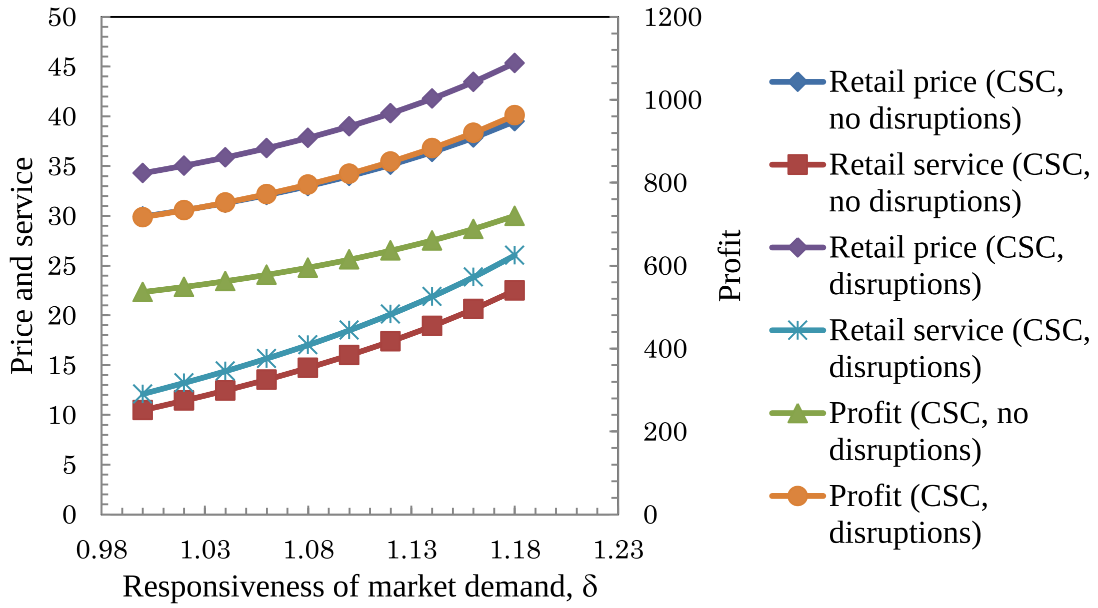

Fig. 6.6 The variation of retail price, retail service, and total profit when δ increases in the centralized supply chain

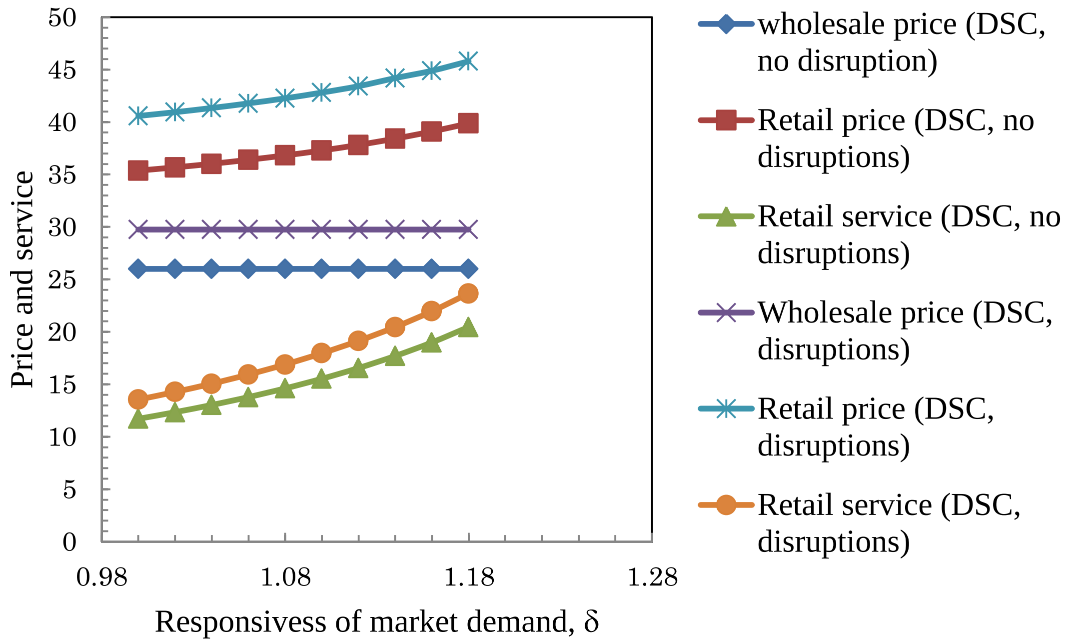

Fig. 6.7 The variation of wholesale price, retail price and retail service when δ increases in the decentralized supply chain

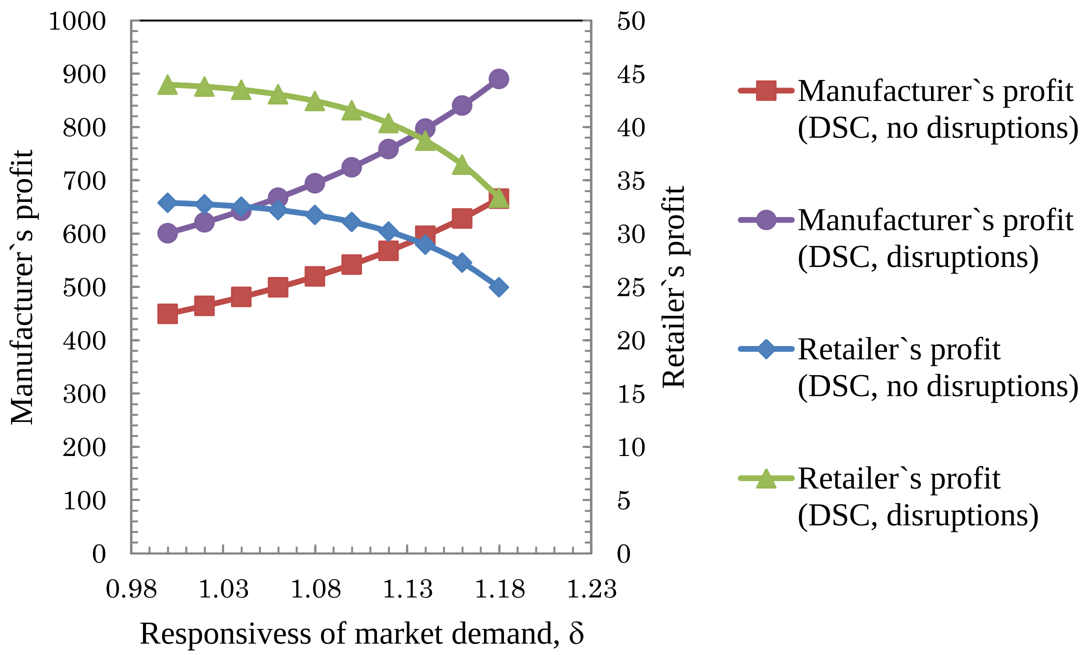

Fig. 6.8 The change of supply chain agent`s profit when δ increases in the decentralized supply chain

From Figure 6.6, it is observed that the retail price, retail service level, and total profit of the centralized supply chain is increased with the increase of responsiveness of market demand in both normal and increased demand scenario. For the decentralized settings, the retail price and retail service show similar behavior with the increase of responsiveness of market demand as presented in Figure 6.7. However, the wholesale price remains fixed with the variation of δ. The shift in wholesale price is due to the increased market demand. As seen in Figure 6.8, the manufacture`s profit tend to increase with the increase of market responsiveness of the retailers. However, the profit of each retailer declines with the increase of market responsiveness. Since we assume that each added service level increases cost in a quadratic nature, therefore the profit is decreased in the similar manner with the provision of more service to customers by the retailers.

6.5 Conclusions

This chapter presents the analytical and numerical investigations of demand disruptions on the price and service policies of the decision makers in a dual channel supply chain system. Further, the effect of cost and demand disruptions is numerically analyzed.

We at first derive the expressions for pricing and service strategies for the centralized and decentralized dual channel supply chain in a non-disrupted environment. We then extend our formulations with real-time demand disruptions. In the numerical experiment, we first consider different demand disruptions scenarios and examine the behavior of the model in terms of pricing, service, and profit of the supply chain members. Next, we consider both demand and cost disruptions to examine supply chain decisions under similar settings. In contrast to most of the price and service models in supply chain, this study assigns the service providing expenditures to retailers. In sum, this study declares that the original price and service strategies need to be adjusted to mitigate the effect of real-time demand and/or cost disruptions. The original strategies are those that are formed by assuming a disruption free supply chain environment. The responsive price and service level actually depend on the magnitude of demand disruptions. Therefore, for revising the price and service level, it is certainly important to know the information as well as the magnitude of demand and/or cost disruptions.

The work presented here can be a basis for further study in the field of supply chain disruptions management. In the future, the problem could be explored using stochastic demand disruptions. In addition, one could think of extending the model by considering service cost disruption, which is very common in a competitive labor market in today`s supply chain system.

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Chapter 7

Conclusions

7.1 Brief Summary of the Thesis

The objectives of this thesis were to develop frameworks to plan for and respond to disruptions in sourcing decisions of firms. For this purpose, a number of quantitative frameworks are developed herein. We begin the thesis with **Chapter 1** where the motivation and objectives of this research are highlighted.

In **Chapter 2**, a scenario-based supply chain disruptions management framework is proposed by integrating supply and demand disruptions. The framework is a linear programming (LP) problem and determines the ordering portfolio to the selected set of suppliers in a pre-disruption and post-disruption situation. Further, the model tries to capture the quality and delivery performance of the suppliers. Costs such as normal and emergency purchasing cost, and inventory holding cost are used to constitute the model. We minimize the sum of purchasing cost, and the expected cost in the event of possible disruptions. The supply and demand scenarios are characterized by the intensity of disruptions. The application of the proposed framework is illustrated through a hypothetical case study. A sensitivity analysis is also conducted with respect to the standard deviation of demand as well as the percentage of order supplied by the respective supplier.

Chapter 3 presents an analytical framework for supply chain disruptions planning of a multi-agent, multi -product supply chain with an emphasis on Conditional Value at Risk (CVaR) as a risk measure. In a risk-neutral operating condition, the decision maker seeks to minimize the expected cost. On the contrary, a risk-averse decision maker wants to minimize the expected worst case cost of a system of interest. Considering the significance of the risk of higher cost in supply chain planning and management, this paper makes an attempt for the minimization of expected worst case cost as a CVaR measure. At the same time, the CVaR model targets to compute the response policies of a supply chain system that undergoes supply and demand disruptions. The proposed formulation is illustrated through some numerical examples. In addition, some computational results are also reported to demonstrate the benefits and applicability of the model in supply chain disruptions planning and decision making process. The results present that the CVaR model shows considerable difference in response policies in comparing with the expected cost model. It is expected that the proposed CVaR model would outperform to optimize the supply chain of an organization, in particular, for the purpose of reducing the risk of high cost.

In **Chapter 4,** we develop an analytical framework of a multiproduct supply chain system composed of multiple suppliers, multiple distribution centers and multiple customers considering disruptions risk. Unlike traditional single sourcing strategy which is mostly discussed in supply chain literature, we apply multi-sourcing strategy in both procurement and distribution of commodities. The model thus developed determines the location of distribution centers from a set of potential location, shipment decisions from multiple suppliers to multiple distribution centers, and shipment decisions from multiple distribution centers to multiple customers. Moreover, the model evaluates the potential amount of products shortages in the event of disruptions. In our work, we consider disruptions at candidate locations for distribution centers (DCs) and to the suppliers. The analytical framework is formulated as a mixed integer programming (MIP) model which minimizes the sum of investment cost, the transportation cost, and the expected shortage cost. Several numerical instances are considered to examine the benefit and practicability of the proposed model. Finally, we compare the results of the risk concern optimization framework to the basic optimization framework, which is designed and built for disruptions free environment. The results of the proposed risk-aware model demonstrate the change of the location of DCs, as well as the shipment decisions compared to the basic model. From the results, it is expected that risk concern model would outperform the basic model in the case of disruptions.

Chapter 5 investigates the coordination problem of a supply chain system composed of one supplier and one retailer. To coordinate, we adopt the approach of revenue sharing contracts in the context of supply chain disruptions management. In this work, we consider two factors disruptions namely demand and service sensitivity coefficient. Thus, we propose a responsive pricing, service level, production and contracts decisions model of the supply chain system within the settings of coordinated framework. The primary aim of coordination is to achieve higher supply chain efficiency in terms of the extent of obtaining centralized supply chain system`s profit. At the same time, coordination requires to ensure win-win conditions for all supply chain partners. It implies that all supply chain partners could obtain higher profit in coordinated settings than they have in decentralized wholesale price contracts. Our results reveal that the proposed coordination mechanisms could lead to the supply chain system achieving around 80-90% efficiency while satisfying the win-win positions of the partners. In addition, this work illustrates that the coordinated supply chain produces more profit to retailer. Our findings also indicate the original contracts for the non-disrupted supply chain system show some level of robustness to the scenarios that show an increase of the market scale and service sensitivity coefficient by small amount. More specifically, the original contracts work fine as long as the increment of market scale is less than 30% of the market base. However, for most of the disruptions scenario, it is seen that the production, pricing, service strategies, and contracts policies need to be adjusted to tackle the disruptions. We show the usefulness and application of our proposed coordination policies by providing some numerical examples.

Chapter 6 studies the price and service competition of a supply chain consisting of one manufacturer and multiple retailers. We take into account real-time demand disruptions at the retail markets. In this system, the retailers outsource product from a fixed supplier and determine their own retail price and service level with an aim to optimize their profit. This could be achieved for the given wholesale price determined by the supplier. The supplier also targets to maximize his profit from the wholesale price. Thus, our works develop a supply chain planning model with an emphasis on demand disruptions. Supply chain decision makers usually determine the optimal retail price, optimal wholesale price, and optimal service level without considering disruptions. However, this plan needs revision in the period when retail markets suffer disruptions due to emergent events. In order to achieve those aims, firstly, we investigate a game theoretical perspective namely Manufacturing Stackelberg (MS) strategy in a decentralized supply chain environment. Next, we examine the optimal retail price and service level under a centralized supply chain setting. The models are illustrated and examined through some numerical insights. Additionally, we numerically investigate the effect of demand and cost disruptions together on the supply chain decisions under similar settings. A sensitivity analysis is also carried out. The findings illustrate that supply chain strategies need to revise to respond to disruptions, as well as to make optimal profit. The findings also conclude that the price and service strategies are highly dependent on the magnitude of demand disruptions. Therefore, it is of great importance to decision makers to know the information of demand disruptions.

7.2 Applications of the Research

At present, supply chain disruptions due to man-made actions are receiving growing attention from many firms due to labor strike or war in different places in the world. Thus, all developed models are expected to apply to firms linked to countries subject to increased man-made supply chain disruptions. Examples of such countries may include Bangladesh, India, and China as well as some countries in Middle East, Europe, and North America. One of the widely known human-made disasters is 9/11 that disrupted many firms including Ford`s production system. A number of Ford`s factories got shutdown due to parts shortages which occurred due to the cancellation of shipment from Canadian suppliers just aftermath of the 9/11 disaster. Recently, global garments supply chain faced huge supply chain disruptions due to some accidents in Bangladesh-fire accident in Tazreen Fashions factory in 2012 and Rana Plaza collapse in 2013. These accidents also reveal some psychological aspects of consumers to make purchasing decision of products importing from Bangladesh. Many firms including Walmart faced crisis as a consequence of these accidents. This research could get special attention to those firms importing garments from Bangladesh. It is noticed that firms linked to China suffer frequent disruptions due to strict tariff rules, communication problems, as well as problems in transferring funds etc. Therefore, those firms doing business with China may also apply the insights of this research to strengthen the supply chain networks for mitigating the disruptions risk.

This research could also be well adapted to firms connected to disaster prone countries such as Japan, Indonesia, Thailand, Taiwan etc. Many automobile and electronic factories are located in these regions and produce and supply parts and products to many countries around the globe. One of the widely cited examples, Japan tsunami 2011 and the global automobile supply chain breakdown may uphold the application of the developed models in real case. Another notable case includes Thailand flood 2011 which caused many electronic factories shutdown during the flood. The technology giant Apple suffered disk drive shortage as a consequence of 2011 Thailand flood. The developed research frameworks in this study may be modified to suit for country specific applications. For example, the firms involved in a specific supply chain network may produce a risk profile by identifying what could go wrong, and how things could go wrong when disasters strike a country. To augment such analysis, the frequency of disasters in a specific country, the average time to recovery from disasters for firms located in that country, and the flexibility of firms to deal with disasters may be useful. The outcome of such analysis could be compiled to our models in order to better identify a backup source, the selection of suppliers and distribution centers location for a supply chain network. Furthermore, price and service strategies, contact strategies would be more realistic by considering a real picture of risk profile of a supply chain network with disaster statistics.

It is hoped that most of the proposed research would possibly fit into consumer product categories such as toys, taints, blankets, video-game, fashion magazine, CD/DVD, garments etc. Besides, some models such as the coordination model established in Chapter 5, and the price and service competition model illustrated in Chapter 6 could be specifically applied in video rental industry as well as online sourcing. This research could also be used for other categories of product with suitable modification of the parameters. Some constraints may also need to modify to suit a specific firm.

This study has some limitations that need to be addressed here. First, one of the major limitations is that hypothetical data are used to test the proposed models. Although some sort of stochasticity is incorporated into some models and those may capture the image of disruptions risks to some extent, further research is needed to test the model using real data for having a broader sense of idea on mitigating disruptions. Second, the proposed research is tested for a limited number of end customers. Apart from this, most of the models assume single time period as well as single disruption. These limitations may restrict the application of this study for real-life disruptions management. Thus, it is advised to fine-tune and revalidate the proposed models to overcome such limitations before its intended application for handling supply chain disruptions.

However, this research is expected to have significant theoretical implications to academics and researchers. The concept introduced in this thesis may be used for refining the theoretical and practical understanding of supply chain disruptions management.

7.3 Future Research Avenues

This study opens several windows for the future research. These issues are delineated below.

Firstly, one probable direction would be to include inventory and safety stock decisions, in addition to procurement and pricing/service decision of firms in facing disruptions. Many firms would like to keep additional inventory or safety stock to mitigate the severity of supply chain disruptions. However, it is important to balance the concern between the inventory holding/safety stock cost and disruptions costs, which may be measured in terms of losing the customer, loss of business reputation and market share etc.

Secondly, we could link the effect of lead time decisions to the mitigation of supply chain disruptions. When supply chain partners have long lead time to transfer the products to the next stage, they get some flexibility to deal with disruptions. Thus, a reduction in lead time makes harder for the partners to recover from disruptions. A simulation study may suit to study the impact of lead time variation on the recovery performance of supply chain.

Thirdly, our study does not explicitly consider transportation disruptions. Therefore, we could extend this study with a focus on transportation disruptions. To mitigate the effect of transportation disruptions, some popular methods such as location routing problem (LRP), vehicle routing problem (VRP), or dynamic vehicle routing problem (DVRP) could be introduced. In addition, the reliability of a transportation mode could also be included in the modeling of transportation disruptions.

Fourthly, this study could also be explored in terms of some well-known phenomena in supply chain such as the bandwagon effect (relates the psychological aspect of buying a product by following/imitating others), bullwhip effect (relates demand and lead time fluctuations), ripple effect (the effect of an event or action propagates throughout the entire supply chain network), and snowball effect (the variability in supply quantities and/or supply delays in any primitive node is strengthened and extended as moved downstream in the supply chain network). For instance, it could be researched how supply and demand disruptions ripple throughout all supply chain nodes in a network and in what extent the disruptions degrade the nodes` performance. A realistic case that forced the ripple effect and snowball effect of the global automobile supply chain is the Japan tsunami in 2011.

Fifthly, it would also be encouraging to identify the effect of supply, demand, and facility disruptions on the sustainability of supply chains. Obviously, disruptions pose negative impacts on the economic, social, and financial indicators of supply chain. Therefore, the research by linking disruptions to the sustainability issues may carry significant theoretical and practical implications.

Finally, it is previously stated that all developed models are tested using a number of synthetic data sets. To enhance the applicability of the developed models, those could be inspected by real data sets from firms. It would be nice if real data sets are collected from Japanese and Bangladeshi firms to verify the models. In so doing, an exemplary conclusion may be deduced on the perspectives of supply chain disruptions management in Japan and Bangladesh. Additionally, variants such as multiple disruptions in a single period, or multiple disruptions with discrete or continuous nature with respect to multiple time periods could be embedded into our proposed models. We look forward to bringing such research theme in the supply chain risk management literature in the future.

Appendix A: Equation for Wholesale Price in Decentralized Supply Chain without Disruption

Manufacturing Stackelberg (MS) wholesale price, $w_i^* = \frac{Q_1}{Q_2}$ where

$$
\begin{aligned}
Q_1 = {} & \left(-\beta_i^2\beta_j^2 c_i\delta_i^2\right)\theta_i^2 \\
& + \big(\alpha_j\beta_i\beta_j^2\delta_i^2\delta_j - \beta_i\beta_j^3 c_j\delta_i^2\delta_j + 2\beta_i^2\beta_j c_i\delta_j^3\gamma_i - 2\alpha_j\beta_i^2\beta_j^2\delta_j k \\
& + 2\beta_i^2\beta_j^3 c_j\delta_j k + \alpha_i\beta_i\beta_j^2\delta_j\gamma_j k - \alpha_i\beta_i\beta_j^2\delta_i\delta_j\theta_j - \beta_i\beta_j^2 c_i\delta_i^2\delta_j\gamma_j \\
& - 2\beta_i^2\beta_j^2 c_i\delta_j\gamma_i k + 3\beta_i^2\beta_j^2 c_i\delta_j\gamma_j k - \beta_i^2\beta_j^2 c_i\delta_i\delta_j\theta_j + 2\alpha_j\beta_i\beta_j\delta_j\gamma_i\gamma_j k \\
& - 2\alpha_j\beta_i\beta_j\delta_i\delta_j\gamma_i\theta_j - 2\beta_i\beta_j c_i\delta_j\gamma_i\gamma_j^2 k - \beta_i\beta_j^2 c_j\delta_j\gamma_i\gamma_j k \\
& + \beta_i\beta_j^2 c_j\delta_i\delta_j\gamma_i\theta_j + 2\beta_i\beta_j c_i\delta_i\delta_j\gamma_i\gamma_j\theta_j\big)\theta_i + 8c_i\beta_i^3\beta_j^3 k^2 \\
& - 4c_i\beta_i^3\beta_j^2\delta_j^2 k - 4c_i\beta_i^2\beta_j^3\delta_i^2 k - 2c_j\beta_i^2\beta_j^3\delta_i k\theta_j - 2c_j\beta_i^2\beta_j^3\gamma_j k^2 \\
& + 8\alpha_i\beta_i^2\beta_j^3 k^2 + 2c_i\beta_i^2\beta_j^2\delta_i^2\delta_j^2 + 3c_i\beta_i^2\beta_j^2\delta_i\gamma_i k\theta_j \\
& + 2\alpha_j\beta_i^2\beta_j^2\delta_i k\theta_j - 2c_j\beta_i^2\beta_j^2\delta_j^2\gamma_i k - 4\alpha_i\beta_i^2\beta_j^2\delta_j^2 k - c_i\beta_i^2\beta_j^2\gamma_i^2 k^2 \\
& - 9c_i\beta_i^2\beta_j^2\gamma_i\gamma_j k^2 + 6\alpha_j\beta_i^2\beta_j^2\gamma_i k^2 + 2\alpha_j\beta_i^2\beta_j^2\gamma_j k^2 \\
& - c_i\beta_i^2\beta_j\delta_i\delta_j^2\gamma_i\theta_j + 2c_i\beta_i^2\beta_j\delta_j^2\gamma_i^2 k + 3c_i\beta_i^2\beta_j\delta_j^2\gamma_i\gamma_j k \\
& - 2\alpha_j\beta_i^2\beta_j\delta_j^2\gamma_i k - c_i\beta_i^2\delta_j^4\gamma_i^2 + c_j\beta_i\beta_j^3\delta_j^3\theta_j - c_j\beta_i\beta_j^3\delta_i^2\gamma_i k \\
& + 3c_j\beta_i\beta_j^3\delta_i^2\gamma_j k - 4\alpha_i\beta_i\beta_j^3\delta_i^2 k - \alpha_j\beta_i\beta_j^2\delta_i^3\theta_j + c_j\beta_i\beta_j^2\delta_i^2\delta_j^2\gamma_i \\
& + 2\alpha_i\beta_i\beta_j^2\delta_i^2\delta_j^2 + 3c_i\beta_i\beta_j^2\delta_i^2\gamma_i\gamma_j k - 3\alpha_j\beta_i\beta_j^2\delta_i^2\gamma_i k \\
& - c_j\beta_i\beta_j^2\delta_i^2\gamma_i\theta_j^2 - 3\alpha_j\beta_i\beta_j^2\delta_i^2\gamma_j k - \alpha_i\beta_i\beta_j^2\delta_i^2\theta_j^2 + c_j\beta_i\beta_j^2\delta_i\gamma_i^2 k\theta_j \\
& + 3\alpha_i\beta_i\beta_j^2\delta_i\gamma_i k\theta_j - c_j\beta_i\beta_j^2\gamma_i^2\gamma_j k^2 + c_j\beta_i\beta_j^2\gamma_i\gamma_j^2 k^2 \\
& - 3\alpha_i\beta_i\beta_j^2\gamma_i\gamma_j k^2 + \alpha_i\beta_i\beta_j^2\gamma_j^2 k^2 - c_i\beta_i\beta_j\delta_i^2\delta_j^2\gamma_i\gamma_j + \alpha_j\beta_i\beta_j\delta_i^2\delta_j^2\gamma_i \\
& - c_j\beta_i\beta_j\delta_i\delta_j^2\gamma_i^2\theta_j - \alpha_i\beta_i\beta_j\delta_i\delta_j^2\gamma_i\theta_j - 2c_i\beta_i\beta_j\delta_i\gamma_i^2\gamma_j k\theta_j \\
& + 2\alpha_j\beta_i\beta_j\delta_i\gamma_i^2\gamma_j^2 k\theta_j + c_j\beta_i\beta_j\delta_j^2\gamma_i^2\gamma_j k + \alpha_i\beta_i\beta_j\delta_j^2\gamma_i\gamma_j k \\
& + 2c_i\beta_i\beta_j\gamma_i^2\gamma_j^2 k^2 - 2\alpha_j\beta_i\beta_j\gamma_i^2\gamma_j k^2 - c_j\beta_j^3\delta_i^4\gamma_j + \alpha_j\beta_j^2\delta_i^4\gamma_j \\
& + c_j\beta_j^2\delta_i^3\gamma_i\gamma_j\theta_j + \alpha_i\beta_j^2\delta_i^3\gamma_j\theta_j - c_j\beta_j^2\delta_i^2\gamma_i\gamma_j^2 k - \alpha_i\beta_j^2\delta_i^2\gamma_j^2 k,
\end{aligned}
$$

$$
\begin{aligned}
Q_2 = {} & \left(-{\beta_i}^2{\beta_j}^2{\delta_j}^2\right){\theta_i}^2 \\
& + \left(6k{\beta_i}^2{\beta_j}^2\delta_j\gamma_j - 2\theta_j{\beta_i}^2{\beta_j}^2\delta_i\delta_j - 2\gamma_i k{\beta_i}^2{\beta_j}^2\delta_j + 2\gamma_i{\beta_i}^2\beta_j{\delta_j}^3\right. \\
& \left. - 2\beta_i{\beta_j}^2{\delta_i}^2\delta_j\gamma_j + 4\gamma_i\theta_j\beta_i\beta_j\delta_i\delta_j\gamma_j - 4\gamma_i k\beta_i\beta_j\delta_j{\gamma_j}^2\right)\theta_i + 16{\beta_i}^3{\beta_j}^3k^2 \\
& - 8{\beta_i}^3{\beta_j}^2{\delta_j}^2k - 8{\beta_i}^2{\beta_j}^3{\delta_i}^2k + 4{\beta_i}^2{\beta_j}^2{\delta_i}^2{\delta_j}^2 - {\beta_i}^2{\beta_j}^2{\delta_i}^2{\theta_j}^2 \\
& + 6{\beta_i}^2{\beta_j}^2\delta_i\gamma_i k\theta_j - 2{\beta_i}^2{\beta_j}^2\delta_i\gamma_j k\theta_j - {\beta_i}^2{\beta_j}^2{\gamma_i}^2k^2 - 18{\beta_i}^2{\beta_j}^2\gamma_i\gamma_j k^2 \\
& - {\beta_i}^2{\beta_j}^2{\gamma_j}^2k^2 - 2{\beta_i}^2\beta_j\delta_i{\delta_j}^2\gamma_i\theta_j + 2{\beta_i}^2\beta_j{\delta_j}^2{\gamma_i}^2k + 6{\beta_i}^2\beta_j{\delta_j}^2\gamma_i\gamma_j k \\
& - {\beta_i}^2{\delta_j}^4{\gamma_i}^2 + 2\beta_i{\beta_j}^2{\delta_i}^3\gamma_j\theta_j + 6\beta_i{\beta_j}^2{\delta_i}^2\gamma_i\gamma_j k + 2\beta_i{\beta_j}^2{\delta_i}^2{\gamma_j}^2k \\
& - 2\beta_i\beta_j{\delta_i}^2{\delta_j}^2\gamma_i\gamma_j - 4\beta_i\beta_j\delta_i{\gamma_i}^2\gamma_j k\theta_j + 4\beta_i\beta_j{\gamma_i}^2{\gamma_j}^2k^2 - {\beta_j}^2{\delta_i}^4{\gamma_j}^2.
\end{aligned}
$$

Appendix B: Equation for Retail Price and Retail Service in Decentralized Supply Chain without Disruption

Manufacturing Stackelberg (MS) retail price, $p_i^* = \frac{\vartheta_1}{\vartheta_2}$ where

$$\vartheta_1 = \Big(\big(-\beta_i^2\beta_j^2c_i\delta_j^2\big)\theta_i^2$$
$$+ \big(\alpha_j\beta_i\beta_j^2\delta_i^2\delta_j - \beta_i\beta_j^3\delta_i^2\delta_j + 2\beta_i^2\beta_jc_i\delta_j^3\gamma_i - 3\alpha_j\beta_i^2\beta_j^2\delta_jk$$
$$+ 3\beta_i^2\beta_j^3c_j\delta_jk + 2\alpha_i\beta_i\beta_j^2\delta_j\gamma_jk - \alpha_i\beta_i\beta_j^2\delta_i\delta_j\theta_j - \beta_i\beta_j^2c_i\delta_i^2\delta_j\gamma_j$$
$$- 2\beta_i^2\beta_j^2c_i\delta_j\gamma_ik + \beta_i^2\beta_j^2c_i\delta_j\gamma_jk - \beta_i^2\beta_j^2c_i\delta_i\delta_j\theta_j + 4\alpha_j\beta_i\beta_j\delta_j\gamma_i\gamma_jk$$
$$- 2\alpha_j\beta_i\beta_j\delta_i\delta_j\gamma_i\theta_j - 2\beta_i\beta_j^2c_j\delta_j\gamma_i\gamma_jk + \beta_i\beta_j^2c_j\delta_i\delta_j\gamma_i\theta_j$$
$$+ 2\beta_i\beta_jc_i\delta_i\delta_j\gamma_i\gamma_j\theta_j\big)\theta_i + 12\alpha_i\beta_i^2\beta_j^3k^2 - \beta_i^2c_i\delta_j^4\gamma_i^2 + 4\beta_i^3\beta_j^3c_ik^2$$
$$+ \alpha_j\beta_j^2\delta_i^4\gamma_j - \beta_j^3c_j\delta_i^4\gamma_j - 4\alpha_i\beta_i\beta_j^3\delta_i^2 - \alpha_j\beta_i\beta_j^2\delta_i^3\theta_j + \beta_i\beta_j^3c_j\delta_i^3\theta_j$$
$$+ \alpha_i\beta_j^2\delta_i^3\gamma_j\theta_j + 2\alpha_i\beta_i\beta_j^2\delta_i^2\delta_j^2 - 6\alpha_i\beta_i^2\beta_j^2\delta_j^2k - 4\beta_i^2\beta_j^3c_i\delta_i^2k$$
$$- 2\beta_i^3\beta_j^2c_i\delta_j^2k + 9\alpha_j\beta_i^2\beta_j^2\gamma_ik^2 + \alpha_j\beta_i^2\beta_j^2\gamma_jk^2 + 3\beta_i^2\beta_j^3c_j\gamma_ik^2$$
$$- \beta_i^2\beta_j^3c_j\gamma_jk^2 - \alpha_i\beta_i\beta_j^2\delta_i^2\theta_j^2 + 2\beta_i^2\beta_j^2c_i\delta_i^2\delta_j^2 - \beta_i^2\beta_j^2c_i\gamma_i^2k^2$$
$$+ \alpha_j\beta_i\beta_j\delta_i^2\delta_j^2\gamma_i - 3\alpha_j\beta_i\beta_j^2\delta_i^2\gamma_ik - 2\alpha_j\beta_i\beta_j^2\delta_i^2\gamma_jk - 3\alpha_j\beta_i^2\beta_j\delta_j^2\gamma_ik$$
$$- \beta_i\beta_j^3c_j\delta_i^2\gamma_ik + 2\beta_i\beta_j^3c_j\delta_i^2\gamma_jk - 6\alpha_i\beta_i\beta_j^2\gamma_i\gamma_jk^2 - 4\alpha_j\beta_i\beta_j\gamma_i^2\gamma_jk^2$$
$$+ \alpha_j\beta_i^2\beta_j^2\delta_ik\theta_j - \beta_i^2\beta_j^3c_j\delta_ik\,\theta_j + \beta_j^2c_j\delta_i^3\gamma_i\gamma_j\theta_j + \beta_i\beta_j^2c_j\delta_i^2\delta_j^2\gamma_i$$
$$+ 2\beta_i^2\beta_jc_i\delta_j^2\gamma_i^2k - 3\beta_i^2\beta_j^2c_j\delta_j^2\gamma_ik - 3\beta_i^2\beta_j^2c_i\gamma_i\gamma_jk^2 - 2\beta_i\beta_j^2c_j\gamma_i^2\gamma_jk^2$$
$$- \beta_i\beta_j^2c_j\delta_i^2\gamma_i\theta_j^2 + 2\alpha_i\beta_i\beta_j\delta_j^2\gamma_i\gamma_jk - \alpha_i\beta_i\beta_j\delta_i\delta_j^2\gamma_i\theta_j + 3\alpha_i\beta_i\beta_j^2\delta_i\gamma_ik\theta_j$$
$$- \alpha_i\beta_i\beta_j^2\delta_i\gamma_jk\theta_j + 2\alpha_j\beta_i\beta_j\delta_i\gamma_i^2k\theta_j - \beta_i\beta_jc_i\delta_i^2\delta_j^2\gamma_i\gamma_j$$
$$+ 3\beta_i\beta_j^2c_i\delta_i^2\gamma_i\gamma_jk + \beta_i^2\beta_jc_i\delta_j^2\gamma_i\gamma_jk + 2\beta_i\beta_jc_j\delta_j^2\gamma_i^2\gamma_jk$$
$$- \beta_i^2\beta_jc_i\delta_i\delta_j^2\gamma_i\theta_j - \beta_i\beta_jc_j\delta_i\delta_j^2\gamma_i^2\theta_j + 3\beta_i^2\beta_j^2c_i\delta_i\gamma_ik\theta_j$$
$$+ \beta_i\beta_j^2c_j\delta_i\gamma_i^2k\theta_j - 2\beta_i\beta_jc_i\delta_i\gamma_i^2\gamma_jk\theta_j - \beta_i\beta_j^2c_j\delta_i\gamma_i\gamma_jk\theta_j\Big),$$

$$
\begin{aligned}
\vartheta_2 = {} & \left(-\beta_i^2 \beta_j^2 \delta_j^2\right)\theta_i^2 \\
& + \left(6\beta_i^2\beta_j^2\delta_j\gamma_j - 2\theta_j\beta_i^2\beta_j^2\delta_i\delta_j - 2\gamma_i k\beta_i^2\beta_j^2\delta_j + 2\gamma_i\beta_i^2\beta_j\delta_j^3\right. \\
& \left. - 2\beta_i\beta_j^2\delta_i^2\delta_j\gamma_j + 4\gamma_i\theta_j\beta_i\beta_j\delta_i\delta_j\gamma_j - 4\gamma_i k\beta_i\beta_j\delta_j\gamma_j^2\right)\theta_i + 16\beta_i^3\beta_j^3k^2 \\
& - 8\beta_i^3\beta_j^2\delta_j^2 k - 8\beta_i^2\beta_j^3\delta_i^2 k + 4\beta_i^2\beta_j^2\delta_i^2\delta_j^2 - \beta_i^2\beta_j^2\delta_i^2\theta_j^2 + 6\beta_i^2\beta_j^2\delta_i\gamma_i k\theta_j \\
& - 2\beta_i^2\beta_j^2\delta_i\gamma_j k\theta_j - \beta_i^2\beta_j^2\gamma_i^2k^2 - 18\beta_i^2\beta_j^2\gamma_i\gamma_j k^2 - \beta_i^2\beta_j^2\gamma_j^2k^2 \\
& - 2\beta_i^2\beta_j\delta_i\delta_j^2\gamma_i\theta_j + 2\beta_i^2\beta_j\delta_j^2\gamma_i^2k + 6\beta_i^2\beta_j\delta_j^2\gamma_i\gamma_j k - \beta_i^2\delta_j^4\gamma_i^2 \\
& + 2\beta_i\beta_j^2\delta_i^3\gamma_j\theta_j + 6\beta_i\beta_j^2\delta_i^2\gamma_i\gamma_j k + 2\beta_i\beta_j^2\delta_i^2\gamma_j^2k - 2\beta_i\beta_j\delta_i^2\delta_j^2\gamma_i\gamma_j \\
& - 4\beta_i\beta_j\delta_i\gamma_i^2\gamma_j k\theta_j + 4\beta_i\beta_j\gamma_i^2\gamma_j^2k^2 - \beta_j^2\delta_i^4\gamma_j^2.
\end{aligned}
$$

Manufacturing Stackelberg (MS) retail service, $s_i^* = \frac{\sigma_1}{\sigma_2}$ where,

$$
\begin{aligned}
\sigma_1 = {} & \beta_j\delta_i\left(-2c_i\beta_i^3\beta_j\delta_j^2 - c_j\theta_j\beta_i^2\beta_j^2\delta_i - c_j\theta_i\beta_i^2\beta_j^2\delta_j + \alpha_j\theta_j\beta_i^2\beta_j\delta_i + c_j\beta_i^2\delta_j^2\gamma_i\right. \\
& + 2\alpha_i\beta_i^2\beta_j\delta_j^2 + 2c_i\theta_i\beta_i^2\beta_j\delta_j\gamma_j + \alpha_j\theta_i\beta_i^2\beta_j\delta_j + 2c_i\beta_i^2\delta_j^2\gamma_i\gamma_j \\
& + \alpha_j\beta_i^2\delta_j^2\gamma_i + c_j\beta_i\beta_j^2\delta_i^2\gamma_j - \alpha_j\beta_i\beta_j\delta_i^2\gamma_j + c_j\theta_j\beta_i\beta_j\delta_i\gamma_i\gamma_j \\
& + \alpha_i\theta_j\beta_i\beta_j\delta_i\gamma_j + c_j\theta_i\beta_i\beta_j\delta_j\gamma_i\gamma_j - \alpha_i\theta_i\beta_i\beta_j\delta_j\gamma_j - c_j\beta_i\delta_j^2\gamma_i^2\gamma_j \\
& - \alpha_i\beta_i\delta_j^2\gamma_i\gamma_j - 2c_i\theta_i\beta_i\delta_j\gamma_i\gamma_j^2 - 2\alpha_j\theta_i\beta_i\delta_j\gamma_i\gamma_j - c_j\beta_j\delta_i^2\gamma_i\gamma_j^2 \\
& \left. - \alpha_i\beta_j\delta_i^2\gamma_j^2\right) \\
& + \beta_j\delta_i k\left(4c_i\beta_i^3\beta_j^2 - c_j\beta_i^2\beta_j^2\gamma_i - c_j\beta_i^2\beta_j^2\gamma_j - 4\alpha_i\beta_i^2\beta_j^2 - 6c_i\beta_i^2\beta_j\gamma_i\gamma_j\right. \\
& - 3\alpha_j\beta_i^2\beta_j\gamma_i + \alpha_j\beta_i^2\beta_j\gamma_j + c_j\beta_i\beta_j\gamma_i^2\gamma_j + c_j\beta_i\beta_j\gamma_i\gamma_j^2 + 3\alpha_i\beta_i\beta_j\gamma_i\gamma_j \\
& \left. + \alpha_i\beta_i\beta_j\gamma_j^2 + 2c_i\beta_i\gamma_i^2\gamma_j^2 + 2\alpha_j\beta_i\gamma_i^2\gamma_j\right),
\end{aligned}
$$

$$
\begin{aligned}
\sigma_2 = {} & -16\beta_i^3\beta_j^3k^2 + 8\beta_i^3\beta_j^2\delta_j^2k + 8\beta_i^2\beta_j^3\delta_i^2k - 4\beta_i^2\beta_j^2\delta_i^2\delta_j^2 + \beta_i^2\beta_j^2\delta_i^2\theta_j^2 \\
& + 2\beta_i^2\beta_j^2\delta_i\delta_j\theta_i\theta_j - 6\beta_i^2\beta_j^2\delta_i\gamma_i k\theta_j + 2\beta_i^2\beta_j^2\delta_i\gamma_j k\theta_j + \beta_i^2\beta_j^2\delta_j^2\theta_i^2 \\
& + 2\beta_i^2\beta_j^2\delta_j\gamma_i k\theta_i - 6\beta_i^2\beta_j^2\delta_j\gamma_j k\theta_i + \beta_i^2\beta_j^2\gamma_i^2k^2 + 18\beta_i^2\beta_j^2\gamma_i\gamma_j k^2 \\
& + \beta_i^2\beta_j^2\gamma_j^2k^2 + 2\beta_i^2\beta_j\delta_i\delta_j^2\gamma_i\theta_j - 2\beta_i^2\beta_j\delta_j^3\gamma_i\theta_i - 2\beta_i^2\beta_j\delta_j^2\gamma_i^2k \\
& - 6\beta_i^2\beta_j\delta_j^2\gamma_i\gamma_j k + \beta_i^2\delta_j^4\gamma_i^2 - 2\beta_i\beta_j^2\delta_i^3\gamma_j\theta_j + 2\beta_i\beta_j^2\delta_i^2\delta_j\gamma_j\theta_i \\
& - 6\beta_i\beta_j^2\delta_i^2\gamma_i\gamma_j k - 2\beta_i\beta_j^2\delta_i^2\gamma_j^2k + 2\beta_i\beta_j\delta_i^2\delta_j^2\gamma_i\gamma_j - 4\beta_i\beta_j\delta_i\delta_j\gamma_i\gamma_j\theta_i\theta_j \\
& + 4\beta_i\beta_j\delta_i\gamma_i^2\gamma_j k\theta_j + 4\beta_i\beta_j\delta_j\gamma_i\gamma_j^2k\theta_i - 4\beta_i\beta_j\gamma_i^2\gamma_j^2k^2 + \beta_j^2\delta_i^4\gamma_j^2.
\end{aligned}
$$

Appendix C: Equation for Wholesale Price, Retail Price, and Retail Service in Decentralized Supply Chain with Disruption

Manufacturing Stackelberg (MS) wholesale price, $\overline{\mathrm{w}}_{\mathrm{i}}^{*} = \frac{\omega_1}{\omega_2}$ where

$$
\begin{aligned}
\omega_1 = {} & \left(-\beta_i^2\beta_j^2 c_i\delta_j^2\right)\theta_i^2 \\
& + \left(\alpha_j\beta_i\beta_j^2\delta_i^2\delta_j - \beta_i\beta_j^3 c_j\delta_i^2\delta_j + \beta_i\beta_j^2\delta_i^2\delta_j\Delta\alpha_j + 2\beta_i^2\beta_j c_i\delta_j^3\gamma_i \right.\\
& - 2\alpha_j\beta_i^2\beta_j^2\delta_j k + 2\beta_i^2\beta_j^3 c_j\delta_j k - 2\beta_i^2\beta_j^2\delta_j\Delta\alpha_j k + \alpha_i\beta_i\beta_j^2\delta_j\gamma_j k \\
& + \beta_i\beta_j^2\delta_j\Delta\alpha_i\gamma_j k - \alpha_i\beta_i\beta_j^2\delta_i\delta_j\theta_j - \beta_i\beta_j^2\delta_i\delta_j\Delta\alpha_i\theta_j - \beta_i\beta_j^2 c_i\delta_i^2\delta_j\gamma_j \\
& - 2\beta_i^2\beta_j^2 c_i\delta_j\gamma_i k + 3\beta_i^2\beta_j^2 c_i\delta_j\gamma_j k - \beta_i^2\beta_j^2 c_i\delta_i\delta_j\theta_j + 2\alpha_j\beta_i\beta_j\delta_j\gamma_i\gamma_j k \\
& + 2\beta_i\beta_j\delta_j\Delta\alpha_j\gamma_i\gamma_j k - 2\alpha_j\beta_i\beta_j\delta_i\delta_j\gamma_i\theta_j - 2\beta_i\beta_j\delta_i\delta_j\Delta\alpha_j\gamma_i\theta_j \\
& - 2\beta_i\beta_j c_i\delta_j\gamma_i\gamma_j^2 k - \beta_i\beta_j^2 c_j\delta_j\gamma_i\gamma_j k + \beta_i\beta_j^2 c_j\delta_i\delta_j\gamma_i\theta_j \\
& \left. + 2\beta_i\beta_j c_i\delta_i\delta_j\gamma_i\gamma_j\theta_j\right)\theta_i + 8\alpha_i\beta_i^2\beta_j^3 k^2 - \beta_i^2 c_i\delta_j^4\gamma_i^2 + 8\beta_i^3\beta_j^3 c_i k^2 \\
& + 8\beta_i^2\beta_j^3\Delta\alpha_i k^2 + \alpha_j\beta_j^2\delta_i^4\gamma_j - \beta_j^3 c_j\delta_i^4\gamma_j + \beta_j^2\delta_i^4\Delta\alpha_j\gamma_j - 4\alpha_i\beta_i\beta_j^3\delta_i^2 k \\
& - 4\beta_i\beta_j^3\delta_i^2\Delta\alpha_i k - \alpha_j\beta_i\beta_j^2\delta_i^3\theta_j + \beta_i\beta_j^3 c_j\delta_i^3\theta_j - \beta_i\beta_j^2\delta_i^3\Delta\alpha_j\theta_j \\
& + \alpha_i\beta_j^2\delta_i^3\gamma_j\theta_j + \beta_j^2\delta_i^3\Delta\alpha_i\gamma_j\theta_j + 2\alpha_i\beta_i\beta_j^2\delta_i^2\delta_j^2 + 2\beta_i\beta_j^2\delta_i^2\delta_j^2\Delta\alpha_i \\
& - 4\alpha_i\beta_i^2\beta_j^2\delta_j^2 k - 4\beta_i^2\beta_j^3 c_i\delta_i^2 k - 4\beta_i^3\beta_j^2 c_i\delta_j^2 k - 4\beta_i^2\beta_j^2\delta_j^2\Delta\alpha_i k \\
& + \alpha_i\beta_i\beta_j^2\gamma_j^2 k^2 + 6\alpha_j\beta_i^2\beta_j^2\gamma_i k^2 + 2\alpha_j\beta_i^2\beta_j^2\gamma_j k^2 + 2\beta_i^2\beta_j^3 c_j\gamma_i k^2 \\
& - 2\beta_i^2\beta_j^3 c_j\gamma_j k^2 - \alpha_i\beta_j^2\delta_i^2\gamma_j^2 k + \beta_i\beta_j^2\Delta\alpha_i\gamma_j^2 k^2 + 6\beta_i^2\beta_j^2\Delta\alpha_j\gamma_i k^2 \\
& + 2\beta_i^2\beta_j^2\Delta\alpha_j\gamma_j k^2 - \beta_j^2\delta_i^2\Delta\alpha_i\gamma_j^2 k - \alpha_i\beta_i\beta_j^2\delta_i^2\theta_j^2 - \beta_i\beta_j^2\delta_i^2\Delta\alpha_i\theta_j^2 \\
& + 2\beta_i^2\beta_j^2 c_i\delta_i^2\delta_j^2 - \beta_i^2\beta_j^2 c_i\gamma_i^2 j^2 + \alpha_j\beta_i\beta_j\delta_i^2\delta_j^2\gamma_i + \beta_i\beta_j\delta_i^2\delta_j^2\Delta\alpha_j\gamma_i \\
& - 3\alpha_j\beta_i\beta_j^2\delta_i^2\gamma_i k - 3\alpha_j\beta_i\beta_j^2\delta_i^2\gamma_j k - 2\alpha_j\beta_i^2\beta_j\delta_j^2\gamma_i k - \beta_i\beta_j^3 c_j\delta_i^2\gamma_i k \\
& + 3\beta_i\beta_j^3 c_j\delta_i^2\gamma_j k - 3\beta_i\beta_j^2\delta_i^2\Delta\alpha_j\gamma_i k - 3\beta_i\beta_j^2\delta_i^2\Delta\alpha_j\gamma_j k \\
& - 2\beta_i^2\beta_j\delta_j^2\Delta\alpha_j\gamma_i k - 3\alpha_i\beta_i\beta_j^2\gamma_i\gamma_j k^2 - 2\alpha_j\beta_i\beta_j\gamma_i^2\gamma_j k^2 \\
& - 3\beta_i\beta_j^2\Delta\alpha_i\gamma_i\gamma_j^2 k^2 - 2\beta_i\beta_j\Delta\alpha_j\gamma_i^2\gamma_j k^2 + 2\alpha_j\beta_i^2\beta_j^2\delta_i k\theta_j \\
& - 2\beta_i^2\beta_j^3 c_j\delta_i k\theta_j + \beta_j^2 c_j\delta_i^3\gamma_i\gamma_j\theta_j + 2\beta_i^2\beta_j^2\delta_i\Delta\alpha_j k\theta_j + \beta_i\beta_j^2 c_j\delta_i^2\delta_j^2\gamma_i \\
& + 2\beta_i^2\beta_j c_i\delta_j^2\gamma_i^2 k - 2\beta_i^2\beta_j^2 c_j\delta_j^2\gamma_i k + 2\beta_i\beta_j c_i\gamma_i^2\gamma_j^2 k^2 - 9\beta_i^2\beta_j^2\, c_i\gamma_i\gamma_j k^2 \\
& + \beta_i\beta_j^2 c_j\gamma_i\gamma_j k^2 - \beta_i\beta_j^2 c_j\gamma_i^2\gamma_j k^2 - \beta_j^2 c_j\delta_i^2\gamma_i\gamma_j^2 k - \beta_i\beta_j^2 c_j\delta_i^2\gamma_i\theta_j^2 \\
& + \alpha_i\beta_i\beta_j\delta_j^2\gamma_i\gamma_j k + \beta_i\beta_j\delta_j^2\Delta\alpha_i\gamma_i\gamma_j k - \alpha_i\beta_i\beta_j\delta_i\delta_j^2\gamma_i\theta_j \\
& - \beta_i\beta_j\delta_i\delta_j^2\Delta\alpha_i\gamma_i\theta_j + 3\alpha_i\beta_i\beta_j^2\delta_i\gamma_i k\theta_j + 2\alpha_j\beta_i\beta_j\delta_i\gamma_i^2 k\theta_j \\
& + 3\beta_i\beta_j^2\delta_i\Delta\alpha_i\gamma_i k\theta_j + 2\beta_i\beta_j\delta_i\Delta\alpha_j\gamma_i^2 k\theta_j - \beta_i\beta_j c_i\delta_i^2\delta_j^2\gamma_i\gamma_j \\
& + 3\beta_i\beta_j^2 c_i\delta_i^2\gamma_i\gamma_j k + 3\beta_i^2\beta_j c_i\delta_j^2\gamma_i\gamma_j k + \beta_i\beta_j c_j\delta_j^2\gamma_i^2\gamma_j k \\
& - \beta_i^2\beta_j c_i\delta_i\delta_j^2\gamma_i\theta_j - \beta_i\beta_j c_j\delta_i\delta_j^2\gamma_i^2\theta_j + 3\beta_i^2\beta_j^2 c_i\delta_i\gamma_i k\theta_j \\
& + \beta_i\beta_j^2 c_j\delta_i\gamma_i^2 k\theta_j - 2\beta_i\beta_j c_i\delta_i\gamma_i^2\gamma_j k\theta_j,
\end{aligned}
$$

$$
\begin{aligned}
\omega_2 = {} & \left(-\beta_i^2\beta_j^2\delta_j^2\right)\theta_i^2 \\
& + \left(6k\beta_i^2\beta_j^2\delta_j\gamma_j - 2\theta_j\beta_i^2\beta_j^2\delta_i\delta_j - 2\gamma_i k\beta_i^2\beta_j^2\delta_j + 2\gamma_i\beta_i^2\beta_j\delta_j^3\right. \\
& \left. - 2\beta_i\beta_j^2\delta_i^2\delta_j\gamma_j + 4\gamma_i\theta_j\beta_i\beta_j\delta_i\delta_j\gamma_j - 4\gamma_i k\beta_i\beta_j\delta_j\gamma_j^2\right)\theta_i + 16\beta_i^3\beta_j^3k^2 \\
& - 8\beta_i^3\beta_j^2\delta_j^2k - 8\beta_i^2\beta_j^3\delta_i^2k + 4\beta_i^2\beta_j^2\delta_i^2\delta_j^2 - \beta_i^2\beta_j^2\delta_i^2\theta_j^2 + 6\beta_i^2\beta_j^2\delta_i\gamma_i k\theta_j \\
& - 2\beta_i^2\beta_j^2\delta_i\gamma_j k\theta_j - \beta_i^2\beta_j^2\gamma_i^2k^2 - 18\beta_i^2\beta_j^2\gamma_i\gamma_j k^2 - \beta_i^2\beta_j^2\gamma_j^2k^2 \\
& - 2\beta_i^2\beta_j\delta_i\delta_j^2\gamma_i\theta_j + 2\beta_i^2\beta_j\delta_j^2\gamma_i^2k + 6\beta_i^2\beta_j\delta_j^2\gamma_i\gamma_j k - \beta_i^2\delta_j^4\gamma_i^2 \\
& + 2\beta_i\beta_j^2\delta_i^3\gamma_j\theta_j + 6\beta_i\beta_j^2\delta_i^2\gamma_i\gamma_j k + 2\beta_i\beta_j^2\delta_i^2\gamma_j^2k - 2\beta_i\beta_j\delta_i^2\delta_j^2\gamma_i\gamma_j \\
& - 4\beta_i\beta_j\delta_i\gamma_i^2\gamma_j k\theta_j + 4\beta_i\beta_j\gamma_i^2\gamma_j^2k^2 - \beta_j^2\delta_i^4\gamma_j^2.
\end{aligned}
$$

Manufacturing Stackelberg (MS) retail price, $\overline{\mathrm{p}}_{\mathrm{i}}^{\,*} = \frac{\tilde{Q}_1}{\tilde{Q}_2}$ where

$$
\begin{aligned}
\tilde{Q}_1 = {} & \left(-\beta_i^2\beta_j^2 c_i\delta_j^2\right)\theta_i^2 \\
& + \big(\alpha_j\beta_i\beta_j^2\delta_i^2\delta_j - \beta_i\beta_j^3 c_j\delta_i^2\delta_j + \beta_i\beta_j^2\delta_i^2\delta_j\Delta\alpha_j + 2\beta_i^2\beta_j c_i\delta_j^3\gamma_i \\
& - 3\alpha_j\beta_i^2\beta_j^2\delta_j k + 3\beta_i^2\beta_j^3 c_j\delta_j k - 3\beta_i^2\beta_j^2\delta_j\Delta\alpha_j k + 2\alpha_i\beta_i\beta_j^2\delta_j\gamma_j k \\
& + 2\beta_i\beta_j^2\delta_j\Delta\alpha_i\gamma_j k - \alpha_i\beta_i\beta_j^2\delta_i\delta_j\theta_j - \beta_i\beta_j^2\delta_i\delta_j\Delta\alpha_i\theta_j - \beta_i\beta_j^2 c_i\delta_i^2\delta_j\gamma_j \\
& - 2\beta_i^2\beta_j^2 c_i\delta_j\gamma_i k + \beta_i^2\beta_j^2 c_i\delta_j\gamma_j k - \beta_i^2\beta_j^2 c_i\delta_i\delta_j\theta_j + 4\alpha_j\beta_i\beta_j\delta_j\gamma_i\gamma_j k \\
& + 4\beta_i\beta_j\delta_j\Delta\alpha_j\gamma_i\gamma_j k - 2\alpha_j\beta_i\beta_j\delta_i\delta_j\gamma_i\theta_j - 2\beta_i\beta_j\delta_i\delta_j\Delta\alpha_j\gamma_i\theta_j \\
& - 2\beta_i\beta_j^2 c_j\delta_j\gamma_i\gamma_j k + \beta_i\beta_j^2 c_j\delta_i\delta_j\gamma_i\,\theta_j + 2\beta_i\beta_j c_i\delta_i\delta_j\gamma_i\gamma_j\theta_j\big)\theta_i \\
& + 12\alpha_i\beta_i^2\beta_j^3 k^2 - \beta_i^2 c_i\delta_j^4\gamma_i^2 + 4\beta_i^3\beta_j^3 c_i k^2 + 12\beta_i^2\beta_j^3\Delta\alpha_i k^2 + \alpha_j\beta_j^2\delta_i^4\gamma_j \\
& - \beta_j^3 c_j\delta_i^4\gamma_j + \beta_j^2\delta_i^4\Delta\alpha_j\gamma_j - 4\alpha_i\beta_i\beta_j^3\delta_i^2 k - 4\beta_i\beta_j^3\delta_i^2\Delta\alpha_i k - \alpha_j\beta_i\beta_j^2\delta_i^3\theta_j \\
& + \beta_i\beta_j^3 c_j\delta_i^3\theta_j - \beta_i\beta_j^2\delta_i^3\Delta\alpha_j\theta_j + \alpha_i\beta_j^2\delta_i^3\gamma_j\theta_j + \beta_j^2\delta_i^3\Delta\alpha_i\gamma_j\theta_j \\
& + 2\alpha_i\beta_i\beta_j^2\delta_i^2\delta_j^2 + 2\beta_i\beta_j^2\delta_i^2\delta_j^2\Delta\alpha_i - 6\alpha_i\beta_i^2\beta_j^2\delta_j^2 k - 4\beta_i^2\beta_j^3 c_i\delta_i^2 k \\
& - 2\beta_i^3\beta_j^2 c_i\delta_j^2 k - 6\beta_i^2\beta_j^2\delta_j^2\Delta\alpha_i k + 9\alpha_j\beta_i^2\beta_j^2\gamma_i k^2 + \alpha_j\beta_i^2\beta_j^2\gamma_j k^2 \\
& + 3\beta_i^2\beta_j^3 c_j\gamma_i k^2 - \beta_i^2\beta_j^3 c_j\gamma_j k^2 + 9\beta_i^2\beta_j^2\Delta\alpha_j\gamma_i k^2 + \beta_i^2\beta_j^2\Delta\alpha_j\gamma_j k^2 \\
& - \alpha_i\beta_i\beta_j^2\delta_i^2\theta_j^2 - \beta_i\beta_j^2\delta_i^2\Delta\alpha_i\theta_j^2 + 2\beta_i^2\beta_j^2 c_i\delta_i^2\delta_j^2 - \beta_i^2\beta_j^2 c_i\gamma_i^2 k^2 \\
& + \alpha_j\beta_i\beta_j\delta_i^2\delta_j^2\gamma_i + \beta_i\beta_j\delta_i^2\delta_j^2\Delta\alpha_j\gamma_i - 3\alpha_j\beta_i\beta_j^2\delta_i^2\gamma_i k - 2\alpha_j\beta_i\beta_j^2\delta_i^2\gamma_j k \\
& - 3\alpha_j\beta_i^2\beta_j\delta_j^2\gamma_i k - \beta_i\beta_j^3 c_j\delta_i^2\gamma_i k + 2\beta_i\beta_j^3 c_j\delta_i^2 k - 3\beta_i\beta_j^2\delta_i^2\Delta\alpha_j\gamma_i k \\
& - 2\beta_i\beta_j^2\delta_i^2\Delta\alpha_j\gamma_j k - 3\beta_i^2\beta_j\delta_j^2\Delta\alpha_j\gamma_i k - 6\alpha_i\beta_i\beta_j^2\gamma_i\gamma_j k^2 \\
& - 4\alpha_j\beta_i\beta_j\gamma_i^2\gamma_j k^2 - 6\beta_i\beta_j^2\Delta\alpha_i\gamma_i\gamma_j k^2 - 4\beta_i\beta_j\Delta\alpha_j\gamma_i^2\gamma_j k^2 + \alpha_j\beta_i^2\beta_j^2\delta_i k\theta_j \\
& - \beta_i^2\beta_j^3 c_j k\theta_j + \beta_j^2 c_j\delta_i^3\gamma_i\gamma_j\theta_j + \beta_i^2\beta_j^2\delta_i\Delta\alpha_j k\theta_j + \beta_i\beta_j^2 c_j\delta_i^2\delta_j^2\gamma_i \\
& + 2\beta_i^2\beta_j c_i\delta_j^2\gamma_i^2 k - 3\beta_i^2\beta_j^2 c_j\delta_j^2\gamma_i k - 3\beta_i^2\beta_j^2 c_i\gamma_i\gamma_j k^2 - 2\beta_i\beta_j^2 c_j\gamma_i^2\gamma_j k^2 \\
& - \beta_i\beta_j^2 c_j\delta_i^2\gamma_i\theta_j^2 + 2\alpha_i\beta_i\beta_j\delta_j^2\gamma_i\gamma_j k + 2\beta_i\beta_j\delta_j^2\Delta\alpha_i\gamma_i\gamma_j k \\
& - \alpha_i\beta_i\beta_j\delta_i\delta_j^2\gamma_i\theta_j - \beta_i\beta_j\delta_i\delta_j^2\Delta\alpha_i\gamma_i\theta_j + 3\alpha_i\beta_i\beta_j^2\delta_i\gamma_i k\theta_j \\
& - \alpha_i\beta_i\beta_j^2\delta_i\gamma_j k\theta_j + 2\alpha_j\beta_i\beta_j\delta_i\gamma_i^2 k\theta_j + 3\beta_i\beta_j^2\delta_i\Delta\alpha_i\gamma_i k\theta_j \\
& + 2\beta_i\beta_j\delta_i\Delta\alpha_j\gamma_i^2 k\theta_j - \beta_i\beta_j^2\delta_i\Delta\alpha_i\gamma_j k\theta_j - \beta_i\beta_j c_i\delta_i^2\delta_j^2\gamma_i\gamma_j \\
& + 3\beta_i\beta_j^2 c_i\delta_i^2\gamma_i\gamma_j k + \beta_i^2\beta_j c_i\delta_j^2\gamma_i\gamma_j k + 2\beta_i\beta_j c_j\delta_j^2\gamma_i^2\gamma_j k \\
& - \beta_i^2\beta_j c_i\delta_i\delta_j^2\gamma_i\theta_j - \beta_i\beta_j c_j\delta_i\delta_j^2\gamma_i^2\theta_j + 3\beta_i^2\beta_j^2 c_i\delta_i\gamma_i k\theta_j \\
& + \beta_i\beta_j^2 c_j\delta_i\gamma_i^2 k\theta_j - 2\beta_i\beta_j c_i\delta_i\gamma_i^2\gamma_j k\theta_j - \beta_i\beta_j^2 c_j\delta_i\gamma_i\gamma_j k\theta_j,
\end{aligned}
$$

$$
\begin{aligned}
\tilde{Q}_2 = {} & \left(-\beta_i^2 \beta_j^2 \delta_j^2\right)\theta_i^2 \\
& + \big(6k\beta_i^2\beta_j^2\delta_j\gamma_j - 2\theta_j\beta_i^2\beta_j^2\delta_i\delta_j - 2\gamma_i k\beta_i^2\beta_j^2\delta_j + 2\gamma_i\beta_i^2\beta_j\delta_j^3 \\
& - 2\beta_i\beta_j^2\delta_i^2\delta_j\gamma_j + 4\gamma_i\theta_j\beta_i\beta_j\delta_i\delta_j\gamma_j - 4\gamma_i k\beta_i\beta_j\delta_j\gamma_j^2\big)\theta_i + 16\beta_i^3\beta_j^3 k^2 \\
& - 8\beta_i^3\beta_j^2\delta_j^2 k - 8\beta_i^2\beta_j^3\delta_i^2 k + 4\beta_i^2\beta_j^2\delta_i^2\delta_j^2 - \beta_i^2\beta_j^2\delta_i^2\theta_j^2 + 6\beta_i^2\beta_j^2\delta_i\gamma_i k\theta_j \\
& - 2\beta_i^2\beta_j^2\delta_i\gamma_j k\theta_j - \beta_i^2\beta_j^2\gamma_i^2 k^2 - 18\beta_i^2\beta_j^2\gamma_i\gamma_j k^2 - \beta_i^2\beta_j^2\gamma_j^2 k^2 \\
& - 2\beta_i^2\beta_j\delta_i\delta_j^2\gamma_i\theta_j + 2\beta_i^2\beta_j\delta_j^2\gamma_i^2 k + 6\beta_i^2\beta_j\delta_j^2\gamma_i\gamma_j k - \beta_i^2\delta_j^4\gamma_i^2 \\
& + 2\beta_i\beta_j^2\delta_i^3\gamma_j\theta_j + 6\beta_i\beta_j^2\delta_i^2\gamma_i\gamma_j k + 2\beta_i\beta_j^2\delta_i^2\gamma_j^2 k - 2\beta_i\beta_j\delta_i^2\delta_j^2\gamma_i\gamma_j \\
& - 4\beta_i\beta_j\delta_i\gamma_i^2\gamma_j k\theta_j + 4\beta_i\beta_j\gamma_i^2\gamma_j^2 k^2 - \beta_j^2\delta_i^4\gamma_j^2.
\end{aligned}
$$

Manufacturing Stackelberg (MS) retail service level, $\bar{s}_i^* = \frac{\tau_1}{\tau_2}$ where

$$\tau_1 = \beta_j\delta_i\big(2\alpha_i\beta_i^2\beta_j\delta_j^2 - 2\beta_i^3\beta_jc_i\delta_j^2 + 2\beta_i^2\beta_j\delta_j^2\Delta\alpha_i - \alpha_i\beta_j\delta_i^2\gamma_j^2 + \alpha_j\beta_i^2\delta_j^2\gamma_i - \beta_j\delta_i^2\Delta\alpha_i\gamma_j^2 + \beta_i^2\delta_j^2\Delta\alpha_j\gamma_i + \beta_i\beta_j^2c_j\delta_i^2\gamma_j + \beta_i^2\beta_jc_j\delta_j^2\gamma_i + 2\beta_i^2c_i\delta_j^2\gamma_i\gamma_j - \beta_ic_j\delta_j^2\gamma_i^2\gamma_j - \beta_jc_j\delta_i^2\gamma_i\gamma_j^2 - \beta_i^2\beta_j^2c_j\delta_i\theta_j - \beta_i^2\beta_j^2c_j\delta_j\theta_i - \alpha_j\beta_i\beta_j\delta_i^2\gamma_j - \beta_i\beta_j\delta_i^2\Delta\alpha_j\gamma_j - \alpha_i\beta_i\delta_j^2\gamma_i\gamma_j - \beta_i\delta_j^2\Delta\alpha_i\gamma_i\gamma_j + \alpha_j\beta_i^2\beta_j\delta_i\theta_j + \alpha_j\beta_i^2\beta_j\delta_j\theta_i + \beta_i^2\beta_j\delta_i\Delta\alpha_j\theta_j + \beta_i^2\beta_j\delta_j\Delta\alpha_j\theta_i + 2\beta_i^2\beta_jc_i\delta_j\gamma_j\theta_i - 2\beta_ic_i\delta_j\gamma_i\gamma_j^2\theta_i + \alpha_i\beta_i\beta_j\delta_i\gamma_j\theta_j - \alpha_i\beta_i\beta_j\delta_j\gamma_j\theta_i + \beta_i\beta_j\delta_i\Delta\alpha_i\gamma_j\theta_j - \beta_i\beta_j\delta_j\Delta\alpha_i\gamma_j\theta_i - 2\alpha_j\beta_i\delta_j\gamma_i\gamma_j\theta_i - 2\beta_i\delta_j\Delta\alpha_j\gamma_i\gamma_j\theta_i + \beta_i\beta_jc_j\delta_i\gamma_i\gamma_j\theta_j + \beta_i\beta_jc_j\delta_j\gamma_i\gamma_j\theta_i\big) + \beta_j\delta_ik\big(4\beta_i^3\beta_j^2c_i - 4\alpha_i\beta_i^2\beta_j^2 - 4\beta_i^2\beta_j^2\Delta\alpha_i + \alpha_i\beta_i\beta_j\gamma_j^2 - 3\alpha_j\beta_i^2\beta_j\gamma_i + \alpha_j\beta_i^2\beta_j\gamma_j + \beta_i\beta_j\Delta\alpha_i\gamma_j^2 - 3\beta_i^2\beta_j\Delta\alpha_j\gamma_i + \beta_i^2\beta_j\Delta\alpha_j\gamma_j + 2\alpha_j\beta_i\gamma_i^2\gamma_j + 2\beta_i\Delta\alpha_j\gamma_i^2\gamma_j - \beta_i^2\beta_j^2c_j\gamma_i - \beta_i^2\beta_j^2c_j\gamma_j + 2\beta_ic_i\gamma_i^2\gamma_j^2 + 3\alpha_i\beta_i\beta_j\gamma_i\gamma_j + 3\beta_i\beta_j\Delta\alpha_i\gamma_i\gamma_j - 6\beta_i^2\beta_jc_i\gamma_i\gamma_j + \beta_i\beta_jc_j\gamma_i\gamma_j^2 + \beta_i\beta_jc_j\gamma_i^2\gamma_j\big),$$

$$\tau_2 = -16\beta_i^3\beta_j^3k^2 + 8\beta_i^3\beta_j^2\delta_j^2k + 8\beta_i^2\beta_j^3\delta_i^2k - 4\beta_i^2\beta_j^2\delta_i^2\delta_j^2 + \beta_i^2\beta_j^2\delta_i^2\theta_j^2 + 2\beta_i^2\beta_j^2\delta_i\delta_j\theta_i\theta_j - 6\beta_i^2\beta_j^2\delta_i\gamma_ik\theta_j + 2\beta_i^2\beta_j^2\delta_i\gamma_jk\theta_j + \beta_i^2\beta_j^2\delta_j^2\theta_i^2 + 2\beta_i^2\beta_j^2\delta_j\gamma_ik\theta_i - 6\beta_i^2\beta_j^2\delta_j\gamma_jk\theta_i + \beta_i^2\beta_j^2\gamma_i^2k^2 + 18\beta_i^2\beta_j^2\gamma_i\gamma_jk^2 + \beta_i^2\beta_j^2\gamma_j^2k^2 + 2\beta_i^2\beta_j\delta_i\delta_j^2\gamma_i\theta_j - 2\beta_i^2\beta_j\delta_j^3\gamma_i\theta_i - 2\beta_i^2\beta_j\delta_j^2\gamma_i^2k - 6\beta_i^2\beta_j\delta_j^2\gamma_i\gamma_jk + \beta_i^2\delta_j^4\gamma_i^2 - 2\beta_i\beta_j^2\delta_i^3\gamma_j\theta_j + 2\beta_i\beta_j^2\delta_i^2\delta_j\gamma_j\theta_i - 6\beta_i\beta_j^2\delta_i^2\gamma_i\gamma_jk - 2\beta_i\beta_j^2\delta_i^2\gamma_j^2k + 2\beta_i\beta_j\delta_i^2\delta_j^2\gamma_i\gamma_j - 4\beta_i\beta_j\delta_i\delta_j\gamma_i\gamma_j\theta_i\theta_j + 4\beta_i\beta_j\delta_i\delta_j\gamma_i^2\gamma_jk\theta_j + 44\beta_i\beta_j\delta_j\gamma_i\gamma_j^2k\theta_i - 4\beta_i\beta_j\gamma_i^2\gamma_j^2k^2 + \beta_j^2\delta_i^4\gamma_j^2.$$