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MANAGING DISRUPTION RISKS IN GLOBAL SUPPLY CHAINS

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by

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ABSTRACT

Supply chain disruptions from man-made and natural disasters represent the most pressing concern in supply chain management. For global supply chain networks, in which entities are located in different geographical regions and goods are moved through various transportation links, each entity and transportation link present its own disruption risk and vulnerability. A disruption at a supply chain component may lead to the disruption of the entire supply chain network. Supply chain management decisions in the volatile business environments must consider the robustness and resiliency of the network to continue operations.

In this dissertation, we incorporate both robustness and the resiliency in the supply chain management decisions. The robustness is considered at the strategic level, while the resiliency is considered at the tactical level. We develop a disruption risk assessment framework to quantify disruption risk scores of supply chain components (facilities and transportation links). A disruption risk score is determined from a qualitative assessment of three factors: *hazard*, *vulnerability*, and *risk management practice*. We apply the disruption risk assessment framework to quantify the suppliers' disruption risks of a global distribution company and develop disruption risk matrices for the suppliers' facilities and suppliers' transportation links. The assessment could enable the company to better understand their suppliers, to address critical network components, and to prioritize risk management activities.

Next, we use the quantified disruption risk scores as disruption risk parameters for the supply chain optimization models. We formulate a multi-criteria strategic model for a global supply chain network design. We solve the multi-criteria model using goal programming. A numerical example is provided to illustrate the robustness of the supply chain network by incorporating disruption risk in the supply chain network design decisions.

Even though the robustness of a supply chain network has been considered at the strategic level, risks still exist. A disruption at a supply chain component may occur at any time during the planning horizon. We formulate a multi-period tactical supply chain model based on the strategic decisions taken during the design phase to evaluate how the disruption at a supply chain component impacts the supply chain network profit and the demand fulfillment. The supply chain network is subjected to a vulnerability analysis and risk mitigation assessment to evaluate the resiliency of the supply chain network operations under disruptions. Finally, we apply risk mitigation strategies, such as extra inventory and backup supplier, to increase the supply chain

network resilience. Decision tree analysis is used to evaluate the cost and benefit among the various risk mitigation strategies.

The strategic model illustrates that a supply chain network design that relies heavily on maximizing profit may create a network characterized by high disruption risk. Considering disruption risk in a strategic supply chain decision enhances the robustness of a supply chain network. The tactical model enables the resiliency improvement of an existing supply chain network. From the numerical example, all three risk mitigation strategies (use of backup supplier, keep extra raw material inventory, and have both backup supplier and extra inventory) increase the ability of a supply chain to bounce back to a stable condition after facing a supplier disruption. Using a backup supplier increases resiliency by providing adequate supply capacity when there is a disruption. Keeping extra raw material inventory temporarily prevents part shortages when facing a short-term disruption. Having both a backup supplier and extra raw material would be an appropriate strategy to mitigate medium-term or long-term disruptions as extra inventory allows a supply chain network to continue its operations until a backup supplier is available. The cost benefit analysis shows that all risk mitigation strategies are attractive. The mitigation costs are much less than the mitigation benefits and the supply chain profits with mitigation strategies are higher than those without any mitigation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Acknowledgements

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Chapter 1

Introduction and Motivation

1.1 Introduction

Disruptions due to man-made and natural disasters have become the top risk concerns for business sectors based on the survey reports by Aon plc (2013), Harvard Business Review (2011), and World Economic Forum (2010). The storms that hit Southeast Asia in 2011 caused the massive floods to Thailand, the major production, supply-base, and export hub for global automakers (e.g., Toyota, Ford, Honda, Isuzu) and electronics device makers (e.g., Sony, Western Digital). The floods forced many plants to suspend production or shut down. The massive 8.9 magnitude earthquake and subsequent tsunami that hit Japan in March 2011 caused loss of life and mass destruction in business sectors. Sony, Toyota, Nissan and many more companies had to stop their production (Ferrari, 2011) due to the destruction of their manufacturing facilities. The closure of the Thailand International Airport in 2008, a strategic transportation hub in Southeast Asia, due to a political crisis caused $2.6 billion loss to the Thai Logistics Sector, which involves 15,000 companies (Boyson et al., 2010). Electronic components, such as hard disk drives and integrated circuits, were transported by trucks to airports in Malaysia and Singapore. This re-routing drastically increased transportation costs and delays to the supply chain networks.

From a supply chain point of view, these disruptions not only damage domestic industries but also affect the world economy due to globalization (Escaith et al., 2011). The attention towards disruptions in supply chain has increased among researchers and practitioners. To address this issue, we need to capture the phenomena of the disruptions on supply chains in order to help organizations manage their supply chains more efficiently. The concept of risk management has been integrated into the supply chain management literature through the processes of risk identification, risk assessment, and mitigation strategies (Peck & Christopher 2003; Soonhong & Mentzer 2004; Chopra & Medhi 2004; Ritchie & Brindley 2007; Craighead et al., 2007; Handfield & McCormack 2008; Knemeyer et al., 2009; Ravindran & Warsing, 2013). These processes provide conceptual frameworks for practitioners and researchers to understand what should be done to manage supply chains disruptions. However, studies have yet to provide a clear decision making tools for managing supply chain disruptions.

Mathematical modeling is an approach that has been used to quantify risks in supply chains. Researchers have applied several approaches to transform risks into numerical values in order to incorporate them in the decision-making models. Portillo (2009) used a qualitative approach to evaluate risks in a global supply chain network design. Yang (2007), You et al. (2008), Bilsel (2009), Kumar et al. (2010) and Ravindran et al. (2010) applied analytic approaches to quantify risk as a function of impact and occurrence, and then set them as criteria in the mathematical models. The studies that present mathematical models and risk management are still limited due to the complexities of supply chain (both structural and functional), modeling, and uncertainty (Ivanov & Sokolov 2010). The studies related to supply chain management and risk management are summarized in the next section.

1.2 Background

1.2.1 Supply Chain Management Models

"Supply Chain Management" (SCM) has been defined from various perspectives. One of the most comprehensive definitions was presented by Simchi-Levi et al. (2008) as "a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying service level requirements."

From the above definition, it is clear that modeling supply chain problems need to consider the following challenges:

- An integration of all business entities (e.g. suppliers, manufacturers, distributors, third-party logistics providers, and retailers) that have an impact on supply chain performance.
- The involvement of multiple business functions and decisions at the strategic, tactical, and operational levels.
- The satisfaction of customer requirements and system-wide profitability.
- The inherent uncertainty and risk in every supply chain.

Due to the above challenges in supply chain problems, supply chain models need to integrate multiple business functions and involve making trade-off between them (Thomas & Griffin 1996; Min & Zhou 2002). It has been recognized that individual or local optimization models do not necessarily aggregate to achieve the system-wide objectives (Bowersox et al., 2002; Mangan et al., 2008). In addition, many studies consider single-objective models which are insufficient to represent the real issues. Over the years, the development of decision-support models that included multi-objective analysis and considered inter-organizational and inter-functional integration and coordination across the supply chain have increased (Min & Zhou 2002). These days, those models have been extended to consider uncertainties in the business environment. These uncertainties include customer demands, costs, lead times, and others. They are usually predictable using historical data or probabilistic estimation, and then can be included in the models. After the 9/11 attack and many disruptive events, risk from man-made and natural disasters has drawn much attention among practitioners and researchers. Although these types of risks have low probability of occurrence compared to uncertainties mentioned earlier, they can tremendously disrupt the supply chains. Chapter 2 discusses supply chain models that consider risks in more detail.

1.2.2 Risk Management in Supply Chain

Supply chain risks have been classified into two categories: (i) *internal supply chain risks*, such as customer demand, product quality, uncertain lead-time, and (ii) *external supply chain risks*, such as exchange rates, natural disasters, terrorist attacks. (Claypool, 2011; Kleindorfer & Saad, 2005; Klibi et al., 2008; Ravindran & Warsing, 2013). The former category has been addressed in supply chain literature for many decades. Customer demands and delivery lead-time have been found in most literature (Arntzen et al., 1995; Bilsel, 2009; Claypool, 2011; Cohen & Lee, 1989; Dogan & Goetschalckx, 1999; Manikandan, 2008; Sabri & Beamon, 2000; Solo, 2009; Tsiakis et al., 2001). As supply chain operations expand globally, supply chain disruptions from the external risks have also become important (Attai, 2003; Bilsel, 2009; Bowersox et al., 2002; Chopra & Sodhi, 2004; Cohen & Lee, 1989; Handfield & McCormack, 2008; Kleindorfer & Saad, 2005; Manuj & Mentzer, 2008; Monczka et al., 2011; Portillo, 2009; Yang, 2007; Vidal & Goetschalckx, 1997). The purpose of managing disruption risks in supply chains is to improve the robustness and the resiliency of a supply chain network. We summarize below the terms and definitions that are frequently used in supply chain risk management studies:

- *Robustness*: the ability of a supply chain network to withstand a risk event (Asbjornslett, 2009).
- *Resiliency*: the ability of a supply chain network to adapt itself and bounce back to a new stable condition after a disruption (Asbjornslett, 2009).

- *Vulnerability*: a lack of robustness or resiliency of a supply chain network with respect to a risk event (Asbjornslett, 2009).

1.3 Motivation

Motivation for this research comes from an electronic supply chain network that consists of suppliers, manufacturing plants, distribution centers, and customer zones. These entities are located in various countries. Distribution centers are located in various regions to serve demands of worldwide customers. Raw material suppliers and manufacturing plants are usually located in developing countries, such as Thailand, China, and Malaysia, which have supportive infrastructures, low labor cost with good quality, and attractive incentives to investors. Recently, many events from man-made and natural disasters have raised concerns, as they have disrupted the operations of those suppliers, manufacturing facilities, and transportation routes. Some have led to the total disruption of global supply chains. For instance, the airport closure in Bangkok in 2008 caused one month delay of products, and transportation cost was incredibly increased since final products could not be shipped by planes as scheduled. Instead, they were carried by trucks to airports at nearby countries. The manufacturing plants in Thailand were almost shut down because the final products could not be shipped from the plants. In 2011, Thailand's political instability resulted in unpredictable consequences to the massive flood that caused losses of life; many areas including industrial zones were submerged in water for months, with significant disruptions to the global supply chains. As the supply chain network structure of the company expands globally, it becomes fragile to the disruption events.

Based on a literature review in Chapter 2, disruption risks are usually incorporated into the supply chain risk management studies based on their probability of occurrences and impacts. However, these two factors are insufficient to understand the influences of a supply chain disruption. The massive floods in Thailand has evidenced that the vulnerability of a supply chain entity and its country, and the availability of risk management practices to prevent or mitigate disruptions are also important factors in supply chain disruptions.

This thesis aims to answer two research questions:

(i) How to make long-term decisions, such as facility location, supplier selection, etc. by taking disruption risk into account, namely, the design of the global supply chain network?

(ii) How to mitigate supply chain disruption risks for an existing supply chain network, namely, the operation of the global supply chain?

1.4 Research Statement

To answer the two research questions, we set up the research framework as shown in Figure 1.1.

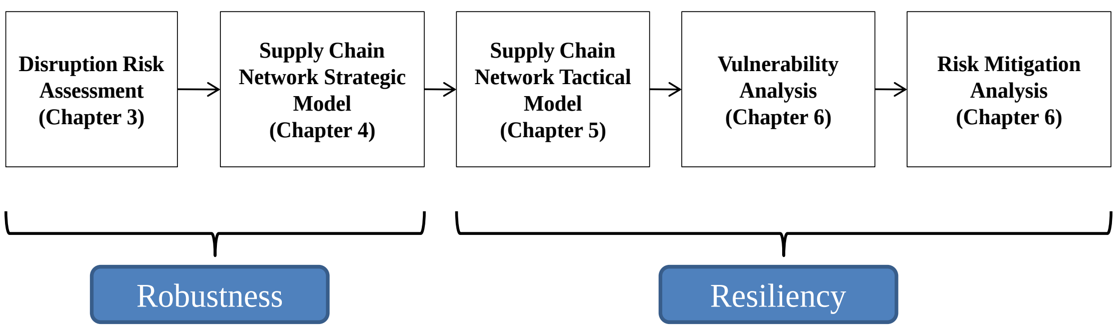


Figure 1.1: Research framework

First, we present a methodology for disruption risk assessment, which is a qualitative assessment process for evaluating the disruption risk scores of facilities and transportation links. The assessment framework is discussed in Chapter 3 illustrated with an actual case study. Next, we apply the quantified disruption risk scores as parameters for the supply chain network strategic model to design a robust supply chain network. The supply chain strategic model is presented in Chapter 4. Since a robust supply chain network may still face disruptions, the supply chain network will be subjected to a vulnerability analysis and risk mitigation assessment. Chapters 5 and 6 are devoted to study the ability of the supply chain network to cope with disruptions and to evaluate risk mitigation strategies. Chapter 5 presents a multi-period supply chain tactical model assuming no disruption. The optimal solution represents a disruption-free scenario under normal operations. Chapter 6 evaluates the impact of a supply chain component disruption to the supply chain network performance. Then, we apply potential risk mitigation strategies, such as keeping extra inventory and using a backup supplier, to demonstrate the improvement to the supply chain performance.

1.5 Contributions

The main contributions of this research are as follows:

1. A disruption risk assessment framework that enables companies to better understand their business partners in term of hazard, vulnerability, and risk management practice. This will facilitate the development of risk mitigation strategies and their cost and benefits.
2. A quantified disruption risk score that allows companies to develop a disruption risk profile of their supply chain components. It can also be used as a disruption risk parameter in supply chain optimization models.
3. A mathematical model that enables firms to make a supply chain network design decision considering disruption risks at the strategic level
4. A mathematical model that allows firms to evaluate the vulnerability of an existing supply chain network and to evaluate the effectiveness of risk mitigation strategies to improve the resilience of a supply chain network operation.

1.6 Structure of the dissertation

Chapter 2 gives a comprehensive review in several related areas including statistical data of natural and man-made disasters, business surveys on managing supply chain disruption, risk management framework, and disaster management. We also discuss the current supply chain literature that incorporates disruption risk in supplier selection, facility location, and supply chain network operations. Chapter 3 presents a qualitative disruption risk assessment method and a case study that applies the quantified disruption risk scores to develop a disruption risk matrix for a company. Chapter 4 presents the use of quantified disruption risk scores as risk parameters for a multi-criteria supply chain network design model. Chapter 5 provides a multi-period supply chain tactical model to determine the optimal purchasing, production, transportation, and inventory that maximize the supply chain profit. Chapter 6 evaluates the vulnerability of the supply chain network when faced with a supply chain component disruption. In Chapter 6, we also study the cost benefits of risk mitigation strategies, such as backup supplier and extra inventory, to demonstrate the improvement to the supply chain performance. Chapter 7 summarizes the dissertation work and points out the areas for further research.

Chapter 2

Literature Review

This chapter provides a review of disruption risk management in supply chains. First, we discuss the importance of supply chain disruptions, including the trends of natural and man-made disasters, the impacts of disruptive events to people and business operations, and the business challenges that have been addressed in business surveys. Next, we provide definitions of the key terms that are frequently used in the supply chain risk management literature. We also review how the risk management framework has been used in the contexts of supply chain management as well as the disaster management to point out some differences. The last section summarizes the supply chain management literature including supplier selection, facility location, and supply chain network design that focus on managing supply chain disruptions.

2.1 Importance of supply chain disruptions

The expansion of supply chain operations through outsourcing and offshoring as well as the increased in risk events worldwide have made supply chains more vulnerable to disruptions. Table 2.1 provides the examples of significant disruption risks and their impacts to global supply chains.

Table 2.1: Disruption risks and their impacts to global supply chains (Powell, 2011; Ruske & Kauschke, 2012)

Year	Country	Risk Event	Economic Impact
2002	United States	West coast port strike	$11-$22 billion
2008	Thailand	Airport closure	$8.5 billion
2010	Worldwide	Piracy and hijacking of ships	$7-$12 billion
2011	Japan	Earthquake/Tsunami	$300 billion
2011	Thailand	Floods	$40 billion
2011	New Zealand	Earthquake	$20 billion
2011	United States	Tornado	$15 billion
2011	Australia	Floods	$7 billion
Annual	Egypt	Ships re-routed to avoid piracy	$642 million from Suez Canal fees

According to the Annual Disaster Statistic Review from the International Disaster Database, there were 332 natural disasters registered in 2011, which killed 30,773 people, caused 244.7 million victims worldwide, and damaged $366.1 billion in economy (Guha-Sapir et al., 2012). From this data, the Japanese earthquake and tsunami in March 2011 caused 19,850 of the death (64.5%) and $210.0 billion of the economic loss (57.4%). The flooding in China during June and September accounted for 159.3 million victims (65.1%). The massive floods in Thailand from August to December 2011 caused more than 800 deaths and 9.5 million victims (3.9%) with a total of $40 billion of damages (10.9%). Based on types of disasters, floods were the largest part in natural disaster occurrence in 2011 (52.1%), followed by storms (25.3%), drought and extreme temperature (11.7%), and earthquakes (10.8%). Among those numbers, 44% of natural disasters occurred in Asia (mainly from floods and earthquakes), which accounted for 86.3% of global disaster victims and 75.4% of global disaster damages in 2011. About 28% of natural disasters occurred in Americas (mainly from storms), which accounted for 18.4% of global disaster damages in 2011. 19.3% of natural disasters occurred in Africa (mainly from floods), which accounted for 9.2% of global disaster victims and about 0.3% of global disaster damages in 2011. Figure 2.1 shows the natural disasters' trends in occurrence and victims from 1900-2011.

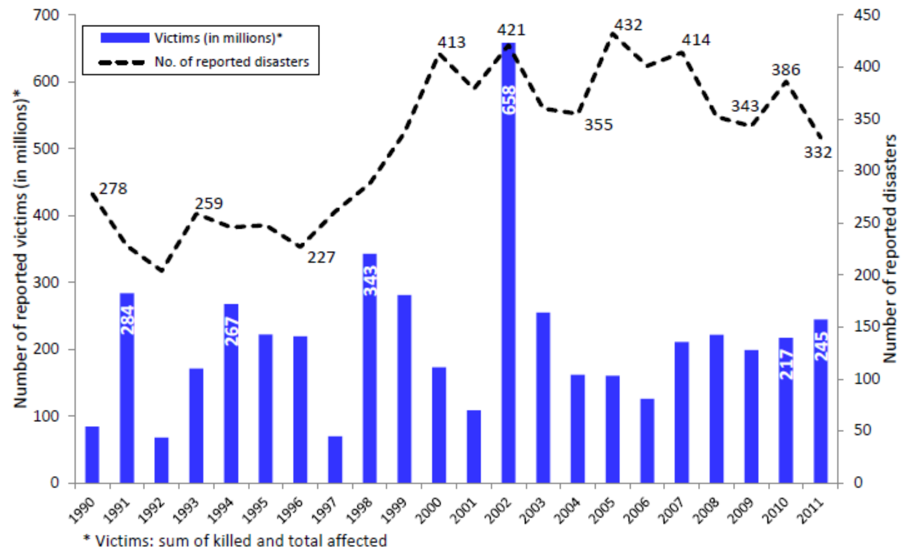


Figure 2.1: Natural disasters' trends in occurrence and victims (Guha-Sapir et al., 2012)

In addition to natural disasters, man-made disasters such as piracy and terrorist attacks are also critical for global supply chain operations. In 2011, there were 439 pirate attacks and 45 merchant vessels hijacked worldwide. More than 50% of these incidents occurred in the Gulf of Aden, off the coast of Somalia, and in the wider Indian Ocean (www.worldshipping.org). A report by the Pricewaterhouse Coopers (PwC) (Ruske & Kauschke, 2012) has also pointed out that gateway regions, geographic features where there is only one narrow way across a strait, or chokepoints that are important for global supply chain are also hot spots of being attacked. Figure 2.2 presents the terrorism threat conditions on maritime sea routes and chokepoints (Ruske & Kauschke, 2012). The coast of Somalia, the Panama canal, and the Strait of Malacca are piracy regions. Several countries, including the United States, have high threat conditions.

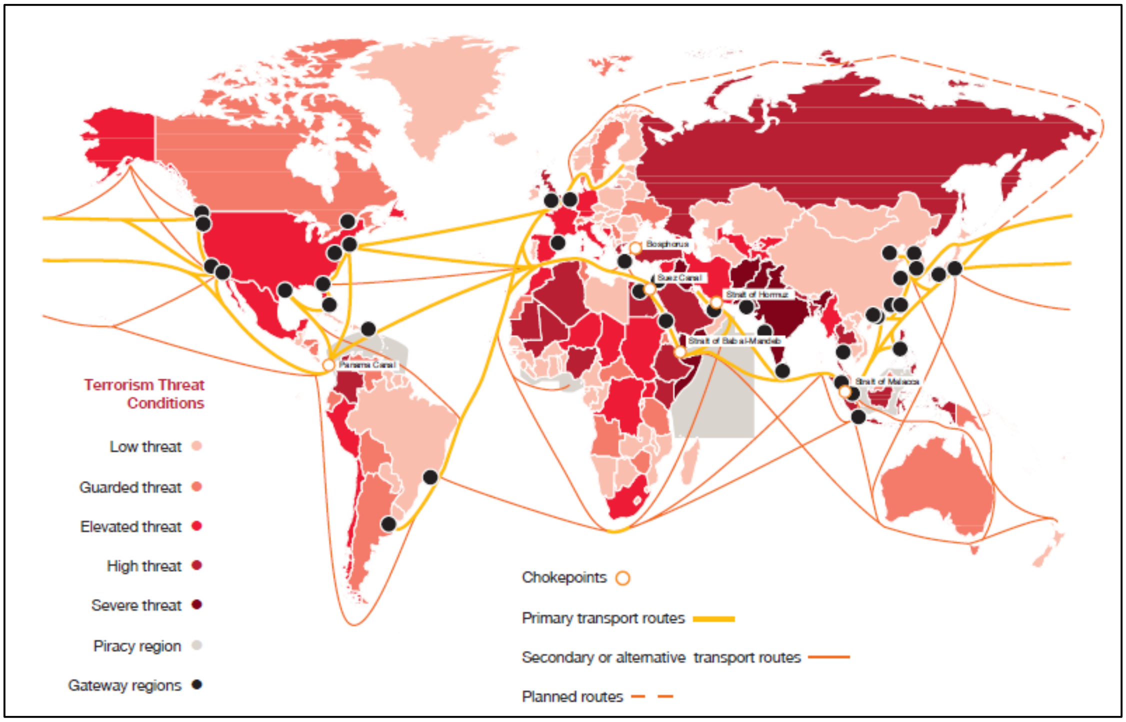


Figure 2.2: Maritime sea routes and crucial chokepoints from Ruske & Kauschke (2012)

In terms of business practitioners' perspectives on supply chain risks, a survey in Harvard Business Review (2011) revealed that over 67% of 1,419 business executives indicated risk management has become more important over the past three years. 89% of the interviewed companies' concerns were natural disasters, such as earthquakes or hurricanes, followed by financial economic crises.

A report by World Economic Forum (2010) has pointed out that natural disasters, conflict and political unrest, sudden demand shocks, export/import restrictions, and terrorism were the top external disruption to supply chains and transportation networks. In addition, reliance on oil, availability of shared data/information, fragmentation along the value chain, extensive subcontracting, and supplier visibility were the top drivers of vulnerability. The report suggested that organizations should consider their manufacturers/suppliers, logistics operators, transportation providers, transportation hubs, retailers, consumers, public, governments, and regulation bodies in order to balance organizations' risk tolerances and risk exposures as part of a systematic risk management process.

According to a survey by Aon plc (2013), over 1,400 organizations world-wide responded that economic slowdown, political uncertainties, weather/natural disasters would be the top risk concerns for next three years. The prolonged Eurozone financial crisis, the slowed growth in China and India, and the uncertainties surrounding the U.S. fiscal policies have affected a company's confidence in the economic recovery and the global financial system. The crisis and turmoil in the Middle East and North Africa, the leadership transition in China, the territorial disputes in South China Sea between Japan and China, and the rising tension in the Korean Peninsula have provoked worries about political risks. The effects from massive flooding in Thailand and Australia, Japanese earthquake and tsunami, the climate change worldwide, and the increase in natural disasters have aggravated worries about natural disasters. The survey has also revealed that, on average, companies' risk readiness has dropped by 7% and the reported loss of income from the top ten risks has increased from 28% in 2011 to 42% in 2013. These could possibly due to inadequate/inefficient risk management planning as well as the prolonged economic recovery that affects companies' abilities to mitigate risks.

2.2 Definitions of Vulnerability, Robustness, and Resilience

This section describes three terms: *vulnerability*, *robustness*, and *resilience* that are frequently used in supply chain risk management studies.

Vulnerability is the degree of inability of a system to cope with the effects of external or internal event that a system is exposed to (Husdal, 2011). Vulnerability of supply chain refers to the properties of a supply chain system that may weaken its ability to endure and survive from disruptive events that originate both within and outside the supply chain (Asbjørnslett, 2009). In other words, vulnerability focuses on the efficiency and adequacy of the available resources to mitigate the system from disruptions.

Robustness is the ability of a supply chain network to resist a threat that may cause negative effects in a supply chain operations and performances (Asbjørnslett, 2009). It is also defined as the ability of a system to perform its function in the presence of failures of components or subsystems (Bundschuh et al., 2003; Klibi and Martel, 2009). The authors measured the supply chain robustness based on the number of supplier failures before a supply chain is completely disrupted and the standard deviation of production quantity that are manufactured during the planning horizon.

Resilience is the ability of a supply network to return to a new stable condition after a threat (Asbjornlett, 2009; Sheffi, 2005), as shown in Figure 2.3. Klibi and Martel (2009) described that resilience is directly related to the supply chain network structure and resources to adapt and bounce back from a disruption quickly.

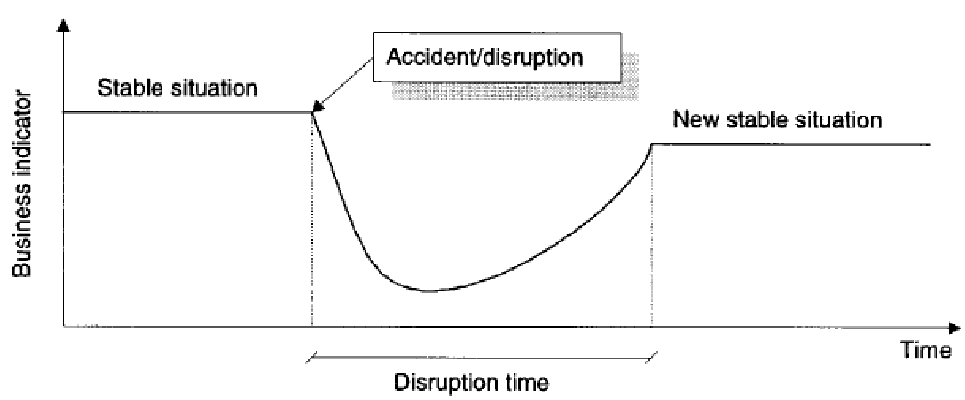


Figure 2.3: Disruption profile of a system from Asbjornlett and Rausand (1997)

2.3 Risk management in supply chains

In today's business environment, supply chain networks are more complex and vulnerable to disruptions. Thus, supply chain disruption has become one of the business challenges to organizations. A well-known supply chain risk management framework is managing risk through the process of: (1) risk identification, (2) risk assessment, (3) risk mitigation, (4) control and evaluation (Chopra & Sodhi, 2004; Cohen & Kunreuther, 2007; Handfield & McCormack, 2008; Manuj & Mentzer, 2008; Sodhi & Tang, 2012; Ravindran & Warsing, 2013).

2.3.1 Risk identification

Risk identification is defining possible risk events, both internal and external, to a supply chain (Ravindran & Warsing, 2013). Companies should understand risks and their driving conditions before selecting appropriate mitigation strategies to reduce negative impacts (Chopra & Sodhi, 2004). In the supply chain risk management literature, supply chain risks are identified based on risk sources/drivers (Juttner et al., 2003; Christopher & Peck, 2004; Bogataj & Bogataj, 2007; Manuj & Mentzer, 2008; Chopra & Sodhi, 2004; Tang & Tomlin, 2008; Kleindorfer & Sadd, 2005) or risk types (Yang, 2007; Viswanadham and Gaonkar, 2008; Oke and Gopalakrishnan, 2009; Ravindran & Warsing, 2013), as shown in Table 2.2.

Table 2.2: Risk classification in current supply chain risk management literature

Authors	Risk identification
	Risk sourcs/drivers
Bogataj & Bogataj (2007)	Supply, process, demand, control
Christopher & Peck (2004)	Supply, process, demand, control, environment
Chopra & Sodhi (2004	Natural disaster, labor dispute, excessive handling due to border crossings or change in transportation nodes. Information breakdown, etc.
Juttner et al., (2003)	Environment, network, organization
Kleindorfer & Sadd (2005)	Operational, natural hazards, terrorism, political instability
Manuj & Mentzer (2008)	Supply, operation, demand, security, and currency
Ravindran & Warsing (2013)	Internal risks, external risks
	Hazard risks, operational risks, financial risks, strategic risks
Tang & Tomlin (2008)	Supply, process, demand, intellectual property, behavior, politica/social
Walters & Rainbird (2007)	International operations, outsourcing, globalization, agile logistics
	Risk types
Klibi & Martel (2009)	Randomness, hazard, deep uncertainty
Oke & Gopalakrishnan (2009)	High frequency- Low impact, Low frequency-High impact
Viswanadham & Gaonkar (2008)	Deviation, Disruption, Disaster
Yang (2006)	Miss-the-Target (MtT), Value-at-Risk (VaR)

2.3.2 Risk assessment

Risk assessment is typically analyzing the impact of disruptions to supply chain operations (Ravindran & Warsing, 2013). One common approach to assess risk is measuring likelihood of occurrence and potential consequences (Dani, 2008; Knemeyer et al., 2009). Bigun (1995) estimated the occurrence of civil aircraft accidents in Europe using expert opinion and historical data; Major (2002) used game theory to estimate the risk of terrorist attack; Wilson (2007) used a simulation technique to estimate impact of supply chain disruption, while Goh et al. (2007) used a multi-stage stochastic model. Wu et al. (2007) proposed a Disruption Analysis Network (DA_NET) to model the propagation of disruptions in a supply chain. Another risk assessment approach is based on the concept of Failure Mode and Effect Analysis (FMEA), where the failure is evaluated based on risk components: severity, occurrence, and detection. Tuncel and Alpan (2010) assessed risks for suppliers, inbound and outbound logistics, manufacturer, and customers using subjective scoring concept called Failure Mode, Effects and

Criticality Analysis (FMECA). The authors defined risk as a function of severity, occurrence, and detection. Ravindran and Warsing (2013) provided a qualitative approach called risk mapping process to measure risk occurrence and risk impact into a 2x2 matrix. The important of risk events are determined based on where in the matrix that the risk falls into. For instance, the risk events that fall into the high-chance and high-impact are the most important risks which deserve the most and immediate attention, whereas the risk events that fall in to the low-chance and low-impact need the least attention. The authors also suggest the risk prioritization method to prioritize risk events in each category. The priority is assigned based on Risk Priority Number (RPN). The RPN is calculated from the product of four risk factors: occurrence, impact, detection, and recovery. The higher RPN value, the more critical the risk is.

Another dimension of risk assessment appeared in recent supply chain risk management literatures is evaluating conditions of supply chain and transportation network that influence a disruption, namely *vulnerability analysis*. The concept of vulnerability was initially used in the social sciences. It has been expanded to other fields such as transportation, economics, information system, disaster management, including supply chain management. Asbjørnslett (2009) described the purposes of vulnerability analysis as follows:

- Understand the nature and types of factors that may cause danger to supply chain system's mission
- Understand the scenarios that involve risks and vulnerabilities
- Understand how the vulnerability scenarios, the likelihood and consequences of risks can be reduced and managed in a cost effectiveness manner

We summarize the drivers of supply chain vulnerability from Asbjornslett (2009), Craighead et al. (2007), Normann and Lindroth (2004), Peck (2005), Wagner and Neshat (2010), Xiaoyan and Xiaofei (2012), as shown in Table 2.3.

Table 2.3: Drivers of supply chain vulnerability

Authors	Drivers of supply chain vulnerability
Asbjornslett (2009)	- Internal factors (e.g. management, technical, system, staff, maintenance, etc.) - External factors (e.g. financial, infrastructure, societal, legal, market, environmental)
Craighead et al. (2007)	- Design characteristics: supply chain density, supply chain complexity, node criticality - Mitigation capabilities: recovery and warning
Norrmann and Lindroth (2004)	- Unit of analysis (from activity level to supply chain network level), - Risk type (from operational level to strategic level), - Stage of risk management activities (from risk identification to business continuity management).
Peck (2005)	- Workflow and information flow e.g. lean manufacturing, agile, demand-driven logistics - Asset and infrastructure dependencies including transportation network - Organization and inter-organizational networks e.g. contract, trading relationships - Environment e.g. social, political, economic, technological, and natural environment
Wagner and Neshat (2010)	- Demand: Product's life cycle, customers' dependency, low in-house production - Supply: small supply base, suppliers' dependency, single sourcing - Supply Chain Structure: global sourcing network, lean inventory, supply chain complexity, centralized storage of finished products
Xiaoyan and Xiaofei (2012)	- Vulnerability assessment is to evaluate condition of a specific region to cope or avoid the hazard, this assessment is based on geographical factors and socio-economic factors

In other studies, vulnerability analysis is also used in for the following purposes:

- Evaluate the impacts of disruptions to network operations in order to design survivable networks or fortify existing networks (Jiang, 2011)
- Study topological characteristics of nodes in a network to disruptions (Zhao et al., 2011)
- Identify critical nodes based on worst case disruptions (Matisziw and Murray, 2008)
- Identify critical nodes or links based on all possible disruption scenarios for a network (Matisziw et al., 2009)

2.3.3 Risk mitigation

Once risks are evaluated and identified, companies shall take appropriate actions to reduce or prevent those risks. Handfield and McCormack (2008) suggested the following risk mitigation strategies to reduce risks in global sourcing.

- Excess resources (e.g. inventory, lead-time, people, suppliers, etc.)
- Supply chain planning and collaboration
- Set up disruption visibility system to ensure timely response to disruptions
- Supply chain redesign (e.g. network redesign and product/process redesign)

Knemeyer et al. (2009) provided a catastrophic risk management matrix based on levels of probability of catastrophic event and estimated loss, as follows:

- Low probability – Low loss: Accept Risk and Loss as the loss may cost less than the risk countermeasure
- Low probability – High loss: Mitigate Loss
- High probability – Low loss: Mitigate Risk
- High probability – High loss: Mitigate Risk and Loss

Norrman and Jansson (2004) and Ravindran and Warsing (2013) summarized practical risk management strategies as follows:

- Take the risk: e.g., carry excessive inventory
- Share the risk: e.g., share risk with partners
- Transfer the risk: e.g., make suppliers to assume all the risk
- Reduce the risk: e.g., take action to minimize impact of risk
- Eliminate the risk: e.g., redesign manufacturing process
- Risk monitoring: e.g., real-time monitoring of suppliers' performance

A company should consider pros and cons of a risk mitigation strategy. Chopra and Sodhi (2004) provided a matrix, as shown in Figure 2.4, of mitigation strategies and risks to indicate how each mitigation strategy affects each risk type. For instance, having additional inventory at warehouse helps to reduce damages from disruption or delay from factory. Unfortunately, it increases costs and might increase risk of having excessive inventory if it cannot be sold.

Mitigation Strategy	Disruptions	Delays	Forecast	Procurement	Receivable	Capacity	Inventory
Add capacity		DD		D		II	D
Add inventory	D	DD		D		D	II
Have redundant suppliers	DD			D		I	D
Increase responsiveness		DD	DD				DD
Increase flexibility		DD		D		DD	D
Aggregate or pool demand			DD			DD	DD
Increase capability		D					D
Have more customer account					D		

D : Decrease Risk　　I : Increase Risk

DD : Greatly Decrease Risk　　II : Greatly Increase Risk

Figure 2.4: Relationship matrix for mitigation strategies and risks (adapted from Chopra and Sodhi, 2004)

The authors also suggested that companies shall evaluate trade-off between risk reductions and reward when implementing risk mitigation strategies. The cost of mitigation shall not outweigh the costs of risk.

2.4 Disaster Risk Management

Disaster risk management typically consists of two phases: the pre-disaster phase and the post-disaster phase (Freeman et al., 2003). Pre-disaster phase includes risk identification, risk mitigation, risk transfer, and preparedness, while post-disaster phase included emergency response, rehabilitation, and reconstruction. For the disaster management literature, we refer to the studies in Amendola et al. (2008), Cannon (1994), Coetzee et al. (2003), Freeman et al.

(2003), International Strategy for Disaster Reduction (UN/ISDR, 2012), Santha and Ratheeshkumar (2009), and Weichsegartner (2001).

2.4.1 Risk identification (Hazard and vulnerability identification)

Risk identification in the context of disaster management covers a broader scope than the risk identification in supply chain management. In the disaster management literature, risk identification is identifying possible hazardous events as well as the vulnerability of a system or a community (Freeman et al., 2003; Coetzee et al., 2003). Vulnerability refers to the conditions of physical, social, economic, geographical, and environmental factors, which increase susceptibility of a community to a hazard (Coetzee et al., 2003; Freeman et al., 2003; UN/ISDR, 2012; Weichsegartner, 2001). These conditions need to be assessed for individual, community, and institutional to understand a community's well-being, strength, resilience, self-protection, social protection, and social capital (Cannon, 1994; Santha and Ratheeshkumar, 2009). The vulnerability of an institution or a country plays an important role in disaster risk management. Disasters may be less severe in countries with efficient, transparent, and accountable governments because they engage in both pre-disaster planning and post-disaster recovery planning, making them able to respond to natural disasters better than corrupt governments (Kellenberg & Mobarak, 2008; Stromberg, 2007; Ye & Abe, 2012). The financial conditions and the economic conditions of a country also important for the success of any risk mitigation and preparedness (Amendola et al., 2008). The studies from Kahn (2005), Kellenberg and Mobarak (2008), and Gaiha et al. (2010) have concluded that GDP per capita is related to damage from disruptive events. The authors state that countries in which citizens have low incomes are more vulnerable to disasters than countries in which citizens have higher incomes. Efforts to mitigate the impact of disaster risks in developing countries are less than in developed countries; developing countries often under-invest in protection, whereas developed countries may lower their exposure to disaster risks by improving the quality of institutions, educations, or access to medical care.

2.4.2 Risk analysis (Hazard and vulnerability assessment)

Risk analysis in the context of the disaster risk management covers hazard assessment and vulnerability assessment. Hazard assessment is identifying possible location, severity of natural disaster, and the likelihood of their occurrence within a specific time period in a given area. The following are the on-line resources containing natural disasters data and hazard assessment guidelines:

- The International Disaster Database (EM-DAT) http://www.emdat.be/
- Federal Emergency Management Agency (FEMA) http://www.ready.gov/risk-assessment
- Natural hazard hotspots, GRID-Arendal, United Nations Environment Program (UNEP) http://maps.grida.no/go/graphic/natural-hazard-hotspots-by-risk-type)
- Natural Disaster Hotspots and Vulnerable Countries, The World Bank, http://www.worldbank.org/ieg/naturaldisasters/maps/

Vulnerability assessment is evaluating the conditions of a community or a country that expose to hazardous events. Following are the on-line resources containing country's risk profile, political risk map, economic rating, and financial rating.

- International Federation of Red Cross and Red Crescent Societies (IFRC)
- The UN Office for Disaster Risk Reduction (UNISDR) http://www.preventionweb.net/english/
- AON Political Risk Map, http://www.aon.com/risk-services/political-risk-map2/map/Interactive_Risk_Map/2011_Political_Risk_Map/index.html#

- World Development Indicators (WDI) and Global Development Finance (GDF), World databank, http://databank.worldbank.org/ddp/home.do?Step=1&id=4
- The World Factbook, https://www.cia.gov/library/publications/the-world-factbook/index.html
- Index of Economic Freedom, http://www.heritage.org/Index/

2.4.3 Risk Mitigation

Risk mitigation for the pre-disaster phase is identifying policies or activities to reduce either the negative impacts or the vulnerability of the location from plausible hazardous events. The mitigation could be done at either structural level (e.g., building, physical structures, etc.) or nonstructural level (e.g., economic, behavior, education, etc.). Risk mitigation also includes risk transfer, which aims to spread risks to other parties such as insurance, hedge on catastrophic bonds, etc. Risk transfer is usually found in developed countries (Freeman et al., 2003). Another risk mitigation is risk preparedness, which refers to the management capability prior to the disaster occurs. Risk preparedness includes training program, warning system, and identification of evacuation program.

Risk mitigations for the post-disaster phase are emergency response, rehabilitation, and reconstruction (Freeman et al., 2003). Emergency responses are typically short-term actions including rescue, humanitarian assistance, emergency health care, temporary restoration, damage assessment, and mobilization of recovery resources. Rehabilitation and reconstruction are long-term recovery actions, such as reconstruction of damaged critical infrastructure, macroeconomic, budget management, and developing sustainable policies.

From the review, we observe the difference between disaster risk management and supply chain disruption risk management. In the supply chain context, risk management mainly focuses on a risk event. In the disaster management context, risk management considers both of a risk event and the vulnerability of a system.

2.5 Managing Disruption Risk in Supply Chains

In this section, we review the supply chain studies, including supplier selection, facility location, and supply chain network design, that consider disruption risks.

2.5.1 Supplier selection problem

Disruption risks in the context of the supplier selection problem are usually assessed from the occurrence and impact of risks (Bilsel, 2009; Gaonkar & Viswanadham, 2004; Ravindran et al., 2010; Yang, 2007; Wu & Olson, 2008). In some studies, disruption risks are also assessed from the vulnerability of suppliers and countries (Chan et al., 2008; Lee, 2009; Levary, 2008). Disruption risks are quantified using both qualitative and quantitative approaches.

Yang (2007) defined risks into two types: Miss-the-Target (MtT) Risk and Value-at-Risk (VaR). MtT-type risks refer to any missed target performances from suppliers that happen frequently but have low impact, such as delivery time, defective rate, etc. The VaR-type risks refer to rare events with high impact that may disrupt suppliers, such as earthquakes, floods, fires, wars, etc. The author quantified risk as a function of probability of occurrence and impact. The probability of occurrence was quantified using the Poisson distribution while the impact was quantified using the Extreme Value distribution. The quantified risk values were incorporated into a strategic supplier selection model and a supply chain optimization model.

Bilsel (2009) developed multi-criteria supplier selection models for the strategic items under two sourcing strategies; single-sourcing and multiple-sourcing. Risk values of potential suppliers are quantified as a function of impact, occurrence, and detectability; impact and occurrence are quantified using the methods proposed by Yang (2007); and detectability is quantified using the Markov Chain theory. The author included a risk mitigation strategy by assigning backup suppliers. The model consists of four objectives: minimize total operation costs, maximize product quality, minimize procurement lead-time, and minimize losses due to disruption risks. Goal Programming (GP) techniques are used to solve the models.

Ravindran et al. (2010) proposed a risk-adjusted supplier selection model. The model pre-qualifies suppliers to reduce the number of potential suppliers into a manageable size. The evaluation process considers 14 factors, including risks. The model allocates order quantities to the selected suppliers by considering price, lead-time, risk of disruption due to natural events (VaR-type risk), and quality risk (MtT-type risk). MtT-type risk and VaR-type risk are estimated using the models developed by Yang (2007) and Bilsel (2009). The multi-criteria optimization model is solved using GP techniques. The value path approach (VPA) is used to present different solutions with respect to the four objectives. The VPA allowed a decision maker to visualize the trade-offs among different decisions. This study also incorporated quantity discounts in the model, which was applied to a real problem of a global IT company.

Gaonkar and Viswanadham (2004) developed two mathematical models to handle supply chain risks: a strategic-level deviation management model and a strategic-level disruption management model. The strategic-level deviation management model was an integer quadratic optimization model adapted from Markowitz’s mean-variance model for portfolio optimization (Markowitz, 1959). The model determined the optimal supplier selection minimizing both the expected supply chain cost and the variation in total supply chain cost. The strategic-level disruption management model was a mixed-integer programming optimization model, adapted from the credit risk minimization model in financial portfolio management (Markowitz, 1959).

The model determines the optimal supplier selection minimizing the expected shortfall, given the expected probabilities for various supplier disruption scenarios.

Wu and Olson (2008) measured supplier risks in terms of quality acceptance levels and the number of late deliveries, which follow exponential and lognormal distributions, respectively. The authors applied three models: chance-constrained programming (CCP), data envelopment analysis (DEA), and multi-objective programming (MOP) to evaluate supply chain risks associated with the supplier selection decision. The study confirmed that all three models can be used to evaluate supplier selection decisions under uncertainty, as they allowed decision makers to perform trade-off analysis among multiple objectives.

Levary (2008) applied the Analytic Hierarchy Process (AHP) to evaluate and rank the foreign suppliers based on suppliers' reliability, country risk (e.g., political risk, man-made and natural disasters, and currency risk), transportation reliability, and suppliers' supplier reliability. Chan et al. (2008) developed a multi-criteria model for a global supplier selection problem. Risk was one of the selection criteria. The sub-criteria for risk included geographic location, political stability, foreign policies, exchange rates, economic position, terrorism and crime rate. A fuzzy set concept was used to capture the vagueness of a decision maker's preference. Criteria and sub-criteria weights were determined using AHP. Similarly, Lee (2009) proposed a fuzzy analytic hierarchy process (FAHP) model to select suppliers based on four criteria: benefits, opportunities, costs, and risks associated with candidate suppliers. The sub-criteria for risk were capacity limit, price variation, financial profile, supplier performance, reputation, and environment controls.

2.5.2 Facility location

Disruption risks in the context of the facility location problem are typically characterized in probabilistic scenarios. The main purpose was to select robust designs that maximize the supply chain efficiency (Klibi & Martel, 2009). Some studies employed scenario analysis to select locations that minimize financial and transportation impacts, assuming that facilities may fail with given probabilities (Drezner, 1987; Snyder & Daskin, 2005; Snyder et al., 2006). Other facility location studies aimed to identify the most vulnerable facilities, facilities for the fortification, and possible mitigation strategies (Aryanezhad et al., 2010; Church & Scaparra, 2006; Church et al., 2004; Peng et al., 2011). The following facility location studies consider disruption risks.

Drezner (1987) presented two facility location models under random disruption risks. The first model was to minimize the expected demand-weighted travel distance. The second model was the (p,q)-center problem to minimize the maximum cost of locating p facilities, where at most q facilities may fail. In both problems, the customers were assigned to the nearest non-disrupted facilities.

Snyder and Daskin (2005) formulated an incapacitated fixed-charge location model problem (UFLP) and the p-median problem. Both models minimized the weighted sum of two objectives: the cost of the system when no disruptions occur and the expected transportation cost when facing disruptions, which allowed decision makers to analyze trade-off between the two costs. However, the authors assumed that all facilities have the same probability of failure. Berman et al. (2007), Li and Ouyang (2010), and Snyder et al. (2006) studied the model similar to Snyder and Daskin's but relax the equal probability assumption.

Church et al. (2004) proposed the median facility interdiction model and the covering facility interdiction model to determine the set of emergency response facilities which, if disabled, will disrupt service delivery the most. Church and Scaparra (2006) formulated a model to determine the best facilities to fortify, assuming that a supply chain network has resources to prevent disruptions.

Aryanezhad et al. (2010) proposed a non-linear location-inventory model with random disruptions of distribution centers (DCs). The authors examined impacts of the facility disruptions on facility location and inventory decisions. The model suggested assigning multiple DCs, a primary DC and backup DCs to each customer in order to cope with disruptions. The model aimed to minimize costs associated with location, transportation, lost sales, and inventory. A genetic algorithm was used to solve the problem.

Peng et al. (2011) formulated a mixed-integer programming model to design a reliable logistics network subjects to facility disruptions. In this study, the probabilistic information about the disruption was not required. Instead, the model aimed to design the network that satisfies objective under specified scenarios. The model objective was to minimize the total nominal cost, which represented the total cost when no disruptions occur, while restricting the relative regret due to disruption risk using the p-robustness criterion. In other words, the relative regret in each scenario could not exceed the desired robustness level p, where $p>0$. A genetic algorithm is used to solve the problem.

2.5.3 Supply chain network design

Disruption risks in the context of supply chain network design problems can be classified into three broad categories: (i) to design a robust supply chain network (Klibi et al., 2008; Bunschuh et al., 2006; Canbolat et al., 2007; Portillo, 2009), (ii) to evaluate the vulnerability or resilience of a supply chain network due to a disruption (Klibi & Martel, 2012; Wilson, 2007; Manikandan, 2008; Solo, 2009), and (iii) to improve the resilience of supply chain network (Snediker et al., 2008; Klibi and Martel, 2012; Harrison et al., 2013; Schmitt and Singh, 2009).

Robust supply chain network

Bunschuh et al. (2006) integrated disruptions in a multi-echelon supply chain network. The robustness of the network was improved by assigning multiple suppliers to each customer. However, this study does not mention the possibility of disruptions at each supplier.

Canbolat et al. (2007) proposed a multi-criteria model for selecting a country to locate a global manufacturing facility. The authors evaluated risk profile of each country based on exchange rate, inflation, and productivity growth. Candidate countries were ranked based on their strengths and weaknesses.

Portillo (2009) formulated a robust global supply chain network design optimization model. Disruption risk was one of the design criteria and evaluated from facility-specific and country-specific factors. The facility factor represented each facility's performance characteristics, as well as frequency of natural disasters. The country-specific factor was measured based on a company's internal weighted average cost of capital (WACC). The WACC represents an estimate of the domestic cost of capital excluding inflation, based on US-denominated bonds that are used to determine the spread between the United States and foreign countries. The author applied a qualitative assessment approach for assessing the disruption risk. For a comprehensive review of the supply chain network design problem under uncertainty, interested readers are referred to the study in Klibi et al. (2008).

Vulnerability analysis of a supply chain network

We classify the vulnerability analysis studies in three categories: conceptual frameworks (Asbjornslett, 2009; Craighead et al., 2007; Falasca et al., 2008; Norrmann & Lindroth, 2004; Peck, 2005; Xiaoyan & Xiaofei, 2012), empirical study (Wagner & Neshat, 2012), and analytical models (Chaudhuri & Singh, 2012; Jiang, 2011; Lockamy III & McCormack, 2010; Manikandan, 2008; Solo, 2009; Matisziw & Murray, 2008; Matisziw, 2009; Schoenherr et al., 2008; Wilson, 2007; Zhao et al., 2011).

Norrmann and Lindroth (2004) suggested that vulnerability should be analyzed from three dimensions: i) unit of analysis (from activity level to supply chain network level), ii) risk type (from operational level to strategic level), and iii) stage of risk management activities (from risk identification to business continuity management). Peck (2005) suggested that vulnerability analysis should consider four levels: i) supply chain management policy on goods flows and information flows, ii) assets and infrastructure needed to produce and carry the goods and information flow, iii) organizations and inter-organizational networks, and iv) environment. Craighead et al. (2007) pointed out that the design characteristics and the mitigation capabilities of supply chain were critical factors to the severity of supply chain disruptions. The design characteristics included supply chain density, supply chain complexity, and node criticality, while the mitigation capabilities referred to recovery capability and warning capability. Falasca et al. (2008) proposed a decision support framework to assess supply chain resilience. The authors extended the study from Craighead et al. (2007) to evaluate supply chain resilience from three dimensions: supply chain density, supply chain complexity, and node criticality. Resilience was measured from the system’s loss and recovery time from a disruption. The authors also pointed out that supply chain resilience can be improved by reducing the probabilities of disruptions, the consequences of disruptions once they occur, and the time to recover normal performance. Xiaoyan and Xiaofei (2012) presented a conceptual model for assessing natural disaster risk in three steps: i) hazard analysis, ii) vulnerability assessment, and iii) risk assessment. Hazard analysis was to evaluate intensity and probability of natural disaster, which could be done using a subjective rating, or the information diffusion theory. Vulnerability assessment was to evaluate condition of a specific region to cope or avoid the hazard. This vulnerability assessment was based on geographical factors and socio-economic factors. Risk assessment was to present risk in a 5x5 matrix based on the levels of hazard and vulnerability. Asbjornslett, (2009) presented a supply chain vulnerability analysis framework using a 1-4 scale rating method based on the likelihood of scenario, consequences of scenarios, and resources to mitigate.

For an empirical study, Wagner and Neshat (2012) measured vulnerability for various types of firms (e.g. automotive, food and consumer goods, logistics, wholesale and retail, etc.) in Germany using Normal Accident Theory and High Reliability Theory. The study shown that there was a negative relationship between supply chain vulnerability and supply chain performance, while there was a positive relationship between supply chain vulnerability and managerial categories (e.g. logistics importance, supply chain risk planning, and supply chain risk management).

Analytical models for the vulnerability analysis include qualitative assessment using AHP (Chaudhuri & Singh, 2012; Schoenherr et al., 2008; Jiang, 2011), Bayesian network (Lockamy III & McCormack, 2010), mathematical models (Matisziw & Murray, 2008; Manikandan, 2008; Solo, 2009), simulation (Wilson, 2007; Matisziw, 2009; Zhao et al., 2011).

Chaudhuri and Singh. (2012) performed a vulnerability analysis for a new product development considering four risk parameters: supplier involvement, process complexity, logistical complexity, and manufacturing capacity, each parameter also has sub-parameters. AHP was used to assess the risk level, which was defined in linguistic terms (e.g., very low, low, medium, high, and very high). The linguistic assessment was then converted to numerical values, which identify the vulnerable product and vulnerable supplier. Finally, FMEA was used to analyze potential failure mode through the fuzzy data of severity, occurrence, and detection, for each vulnerable supplier. The model was applied to an aerospace industry consisted of 4 suppliers, 4 decision makers, and 4 products.

Schoenherr et al. (2008) applied AHP to assess supply chain risk for supporting the offshore sourcing decision of a US manufacturing company. The authors considered product, partner, and environment as decision criteria. Each criterion consisted of risk factors. Risk factors of the product criterion included ANSI compliance, product quality, product cost, and competitor cost. Risk factors of the partner criterion included demand risk, supplier fulfillment risk, logistics risk, delivery, order fulfillment risk, wrong partner risk, overseas risk, supplier risk, supplier's supplier management, and engineering and innovation. Risk factors of the environment criterion were transportation risk, sovereign risk, and natural disasters or terrorists.

Jiang (2011) applied a scenario analysis for assessing supply chain risk. Risk factors were procurement, production, finance and management. Each factor consisted of sub-factors, and they were evaluated into five levels (extremely high, high, medium, low, and extremely low). Then, risk factor weights were determined using AHP. Next, disruptive scenarios were generated according to possible impacts from a new environment policy in Europe. The author assumed that the new policy may cause impact to supplier and delivery. Four possible disruptive scenarios were generated as follows:

(i) Supplier cannot comply with the new policy – Strict inspection delays the delivery

(ii) Supplier cannot comply with the new policy – Strict inspection does not delay the delivery

(iii) Supplier can comply with the new policy – Strict inspection delays the delivery

(iv) Supplier can comply with the new policy – Strict inspection does not delay the delivery

A fuzzy synthetic evaluation model was used to measure the factors' impact on the supply chain under various scenarios. The contribution of this paper was to help a manager in identifying possible areas of improvement to deal with potential risks.

Lockamy III and McCormack (2010) evaluated outsourcing decisions using Bayesian network. The authors considered supplier's external, operation, network risk probabilities, and revenue impact. Risk profile of a supplier was developed based on relationship factor, supplier past performance factor, human resource factor, history of supply chain disruptions factor, environmental factor (e.g., geographical, market, transportation, etc.), disaster history, and financial factor. The proposed methodology was applied to evaluate casting suppliers in the US automotive industry.

For optimization models, Matisziw and Murray (2008) evaluated the vulnerability of Ohio's interstate highway network to disruption using an interdiction optimization model. The objective was to identify critical infrastructure that, if disabled, results in the most negative impact to the system flow. Manikandan (2008) formulated a mixed-integer, multi-period, deterministic model for a centralized supply chain optimization. Risks such as supplier price fluctuation and cease of a mode of transportation were incorporated in the study.

Solo (2009) developed a two-phase multi-objective optimization model to solve a supply chain network design and distribution problem. The first phase provided strategic decisions such as supplier selection, plant construction, production capacity level, and plant and warehouse operating schedules. The optimal solutions from this phase were used as inputs for the tactical model. The second phase provided tactical decisions such as supplier selection for non-critical raw materials, material order allocation, shipping, and storage quantities, finished product production, storage, and shipping quantities, and optimal profit. Disruption risks were incorporated in the tactical model through the disruption of transportation routes.

For simulation models, Wilson (2007) studied the effect of a transportation disruption for a five-echelon supply chain, which consisted of retailer, warehouse, tier-1 supplier, tier-2 supplier, and raw material supplier. The author compared the disruption effect between a traditional supply chain system and a vender managed inventory (VMI) system using system dynamics simulation. The result indicated that the greatest impact occurred when transportation was disrupted between a tier-1 supplier and a warehouse. In the traditional structure, retailer, warehouse, and tier-1 supplier experienced the greatest inventory fluctuations and had the most goods in transit to their facilities. These impacts were less severe in the VMI structure because the tier-1 supplier determined the number of items to be shipped to the warehouse based on customer demand. However, both structures yielded the same number of unfilled orders due to transportation disruptions.

Matisziw (2009) applied simulation for evaluating vulnerability to disruptions of nodes or links in a communication network. The evaluation processes consisted of (i) set up a network topology and network attributes, (ii) select n scenarios of facilities being disrupted, (iii) assess impacts of network performance for all scenarios, and (iv) find origin-destination pairs that are still connected after disruption has occurred in order to plan for security.

Zhao et al., (2011) used a discrete event simulation to evaluate the resiliency of four military logistics network topologies against random disruptions (e.g., natural disasters, accidents, and unexpected economic events) and targeted disruptions (terrorist and military attacks). The authors characterized the supply network resilience in terms of availability, connectivity, and accessibility. The networks contained 1000 nodes and 1815 edges. The analysis allowed 5% of the total nodes to be removed. The authors assumed that disruptions affected only nodes and the probability of disruptions were known.

Murray et al., (2008) discussed the advantages and limitations four commonly used approaches for assessing network vulnerability on infrastructure planning and policy development: scenario-specific, strategy-specific, simulation, and mathematical modeling, as shown in Table 2.4.

Table 2.4: Network vulnerability assessment (adapted from Murray et al., 2008)

Assessment Method	Description	Benefits	Shortcoming
Scenario-specific	Evaluate consequences of specific or a small set of disruption scenarios	1) Allow detailed understanding on the consequences of each scenario. 2) Important scenarios are readily identified by experts or analytical approaches	1) Limit number of scenarios for evaluating. 2) Not recommend for identifying the potential disruption scenarios relative to the system as a whole.
Strategy-specific	Based on the scenario-specific, evaluate how vulnerability is a network to a loss of facilities in terms of facility important.	1) Useful in assessing vulnerability of different network configurations to an identical attack strategy	1) The assessment is limited on the scenarios considered. 2) The relative importance of network facilities is predefined prior to the analysis. This is possible to produce misleading results. 3) Disruption impact is evaluated according to the same performance criteria for each scenario.
Simulation	To analyze how do disruptive scenarios impact infrastructure operation.	1) Useful when complete scenario enumeration is not an option. 2) Enhance flexibility of analysis 3) Accommodate large-scale network.	1) Difficult to indicate upper bound/lower bound for a large network which has a large range of disruptive scenarios.
Mathematical modeling	To analyze the worst-case or best-case scenarios network operations due to disruptive events without a complete enumeration.	1) Establish bounds on in less computational time compared to complete enumeration and simulation 2) Ability to evaluate the worst case scenario	1) Complexity from network structure and operation may be difficult to model 2) Focus on the worst-case scenario may limit consideration of alternative scenario

Resiliency improvement of a supply chain network

Klibi and Martel (2012) proposed a risk modeling approach, namely *a three-phase hazard model*, to generate plausible future supply chain scenarios. Phase-1 estimates supply chain network uncertainty based on multi-hazards, vulnerability sources, and exposure levels; Phase-2 estimates hazard arrival, intensity, and duration; Phase-3 assesses impact and recovery time. The future uncertainty scenarios are generated using a Monte Carlo approach. The authors applied the risk modeling approach to characterize future supply chain scenarios for two business cases. In case 1, the risk model was used to generate future scenarios for a two-echelon North-American distribution network. The future scenarios were generated to cover a 1-year planning horizon with daily working period under random customer orders and natural catastrophes at distribution centers. In case 2, the risk model was used to generate future scenarios for the Canadian Armed Forces to support its worldwide humanitarian, peacekeeping, and peace enforcement missions. The future scenarios were generated to cover a 10-years planning horizon with weekly working periods under natural catastrophes and global conflicts.

Another study that uses simulation approach is in Matisziw (2009). The author applied simulation for evaluating the vulnerability to disruptions of nodes or links in a communication network. The evaluation processes consisted of: (i) setting up a network topology and network attributes; (ii) selecting the scenarios of facilities being disrupted; (iii) assessing impacts of network performance for all scenarios; and (iv) finding origin-destination pairs that are still connected after disruption has occurred in order to plan for security. Two mitigation strategies considered were protecting the network components (nodes) and adding new links to the network.

Schmitt and Singh (2009) used simulation approach to quantify the supply chain disruption risk of a consumer products company. In their model, the supply chain consisted of suppliers, manufacturing plant, packaging plant, and distribution centers. A Monte Carlo simulation was used to study risk profiles while a Discrete Event Simulation (DES) was used to estimate flow of material and network interactions. Disruptive events followed an exponential inter-arrival time, while duration of disruption was represented by a lognormal distribution. Backup facility, flexible production sizing, and inventory level were used as mitigation strategies.

For the mathematical model approach, Snediker et al. (2008) developed a decision support system for mitigating network disruption. The decision support system examined the effects of different network disruption scenarios using an interdiction model. The authors developed an interface, which allowed visualization of the network and flows. The decision support system also allowed users to analyze mitigation strategies with respect to the disruptive scenarios. Two mitigation strategies are apply protection to the network components (nodes) and to add new links to the network.

Harrison et al. (2013) proposed an optimization approach, namely Resiliency Enhancement Analysis via Deletion and Insertion (READI) to improve supply chain network resiliency. The resiliency enhancement analysis via deletion evaluates the network resiliency when key supply chain node or flow is disabled. The resiliency enhancement analysis via insertion evaluates the mitigation strategy for resilience improvements. READI was used to illustrate the resiliency improvement for a consumer packaged goods firm in North America, which consists of 5 supply facilities, 4 plants, and 13 DCs.

Table 2.5 summarizes the supply chain risk management from our review to provide a comparison of the objectives of this research.

Table 2.5: Summary of the supply chain risk management studies

Authors	Supply Chain Decision	Model objective(s)	Risk factor(s)	Methodology	Consider Decision Maker	Disrupted component (Facility/ Transportation)	Risk Management Focus
Gaonkar & Viswanadham (2004)	Supplier Selection	Expected cost and cost variance	Probability of occurrence, impact	MILP/excel solver	No	Facility/ Transportation	Robustness
Yang (2006)	Supplier Selection	Delivery, Business criteria, Quality, Cost, IT, Improvement	Probability of occurrence, impact	Multi-criteria model/GP	Yes	Facility	Robustness
Chan et al., (2008)	Supplier Selection	Cost. Quality, Service, Supplier Profile, Risk	Location, political instability, foreign policies, exchange rate, economic position, crime rate	Multi-criteria Selection Problem/ Fuzzy AHP	Yes	-	Robustness
Levary (2008)	Supplier Selection	Select the most reliable suppliers	Reliability of transportation, supplier's suppliers, country risk	Raking Method/ AHP	Yes	-	Robustness
Lee (2009)	Supplier Selection	Benefit, opportunity, cost, risk	Price variation, financial profile, capacity, supplier reputation, environment controls	Multi-criteria Problem/Fuzzy AHP	Yes	-	Robustness
Bisel (2009)	Supplier Selection	Cost, Lead-time, Quality, Disruption Risk	Probability of occurrence, impact	Multi-criteria model/GP	Yes	Facility	Robustness/ Resilience
Ravindran et al., (2010)	Supplier Selection	Price, Deviation Risk, Lead-time, Disruption Risk	Probability of occurrence, impact	Multi-criteria model/GP	Yes	Facility	Robustness
Drezner (1987)	Facility Location	Expected demand-weighted travel distance, Cost	Probability of occurrence, impact	P-median, (p,q)-center problem	No	Facility	Robustness
Snyder and Daskin (2005)	Facility Location	Weighted sum of cost and expected failure cost	Probability of occurrence, impact	P-median problem	No	Facility	Robustness
Snyder et al., (2006)	Facility Location	Expected Cost	Probability of occurrence, impact	P-median, R-covering	No	Facility	Vulnerability
Church et al., (2004)	Facility Location	Service delivery	Probability of occurrence, impact	P-median, R-covering	No	Facility	Vulnerability
Aryanezhad et al., (2010)	Facility Location	Costs (location, transportation), lost sales, inventory	Probability of occurrence, impact	Non-linear location-inventory model/Genetic algorithm	No	Facility	Robustness
Peng et al., (2011)	Facility Location	Cost	Robustness level in term of cost	MILP/Genetic algorithm	No	Facility	Robustness

Table 2.5: Summary of the supply chain risk management studies (continued)

Authors	Supply Chain Decision	Model objective(s)	Risk factor(s)	Methodology	Consider Decision Maker	Disrupted component (Facility/ Transportation)	Risk Management Focus
Manikandan (2008)	Supply Chain Network	Cost	Price uncertainty,	MILP	No	Transportation	Vulnerability
Aryanezhad et al. (2010)	Supply Chain Network/Inventory	Costs of location, inventory, transportation, lost sales	Probability of occurrence	Nonlinear IP/Genetic algorithm	No	Facility	Robustness
Bunschuh et al., (2006)	Supply Chain Network	Costs (production, inventory, transportation, contingency supply) and reliability	Cost	Scenario analysis/ Simulation	No	Facility	Robustness
Jiang Fen (2011)	Supply Chain Network	Evaluate impact from a new environment policy in Europe	Procurement, production, finance, management	Scenario Analysis/AHP	Yes	-	Vulnerability
Harrison et al., (2013)	Supply Chain Network	Cost	Node removal	Mathematical programming	No	Facility	Resilience
Matisziw (2009)	Communication network	Network connectivity	Node removal	Simulation/Scenario analysis	No	Facility/ Transportation	Resilience
Matisziw and Murray (2008)	Supply Chain Network	System flow	Link removal	Mathematical Model	No	Facility/ Transportation	Vulnerability
Portillo (2009)	Supply Chain Network	Profit,Customer Service,Risk,Strategic measure	Facility-specific risk, country-specific risk	Multi-criteria model/GP	Yes	Facility	Robustness
Schmitt and Singh (2009)	Supply Chain Network	Demand fulfillment	Probability of occurrence and disruption duration	Simulation	No	Facility	Resilience
Snediker et al. (2008)	Supply Chain Network	Cost, network connectivity	Node removal	Scenario Analysis	No	Facility	Resilience
Solo (2009)	Supply Chain Network	Profit,Shortage,Time	Disruption of transportation	Multi-criteria model/GP	Yes	Transportation	Resilience
Wilson (2007)	Supply Chain Network	Customer fulfillment	Link removal	Simulation	No	Transportation	Vulnerability
Zhao et al. (2011)	Supply Chain Network	Availability, Connectivity, Accessibility	Probability of occurrence	Simulation	No	Facility	Vulnerability/ Resilience
This Thesis	**Supply Chain Network**	**Profit, Demand fulfillment, Delivery time, Disruption Risks**	**Node / Link removal**	**Multi-criteria model/GP**	**Yes**	**Facility/ Transportation**	**Robustness/ Resilience**

Chapter 3

Disruption Risk Assessment

3.1 Introduction

Supply chains disruption has become a pressing concern in businesses. As companies expand their operations globally through outsourcing and off-shoring for competitive efficiency, they become more vulnerable to disruptions. Disruption in one country can seriously impact the global supply chain. The devastating 9.0-magnitude earthquake and tsunami in Japan and the massive flood in Thailand in 2011 are examples of disruptive events that caused profound damages, not only to people's lives and to local economies, but also to global supply chains as these countries are the location of key suppliers of electronic and automotive industries. Another reason that makes supply chains vulnerable to disruptions is that the number of disruptive events reported worldwide, including natural and man-made disasters, is high. The average annual disaster occurrence during 2001-2010 was 384 (Guha-Sapir et al., 2012). Therefore, global supply chains are exposed to various disruptions in the volatile business environment. These events may disrupt the facility and/or the transportation link in a supply chain network, which may lead to the disruption of the entire supply chain. Both practitioners and researchers are motivated to understand the influence of supply chain disruptions and develop strategies to enhance the organizational resiliency in order to ensure business continuity when disruptions occur.

Supply chain network consists of entities (suppliers, manufacturers, distributors, retailers, and customers) and a transportation network that connects the entities to facilitate the physical flow of goods. The links in the transportation network connect specified points of origin and points of destination. For global supply chain networks, where entities are located in different geographical regions and goods are moved through various transportation modes, each entity and transportation link has its own risk and vulnerability that may lead to the disruption of the entire supply chain network. Firms need to consider both risk and vulnerability of their supply chain components when designing the supply chain network in order to balance the business efficiency and risk (Juttner, 2005, Craighead et al., 2007, Wilson, 2007, Asbjornslett, 2009, Ravindran and Warsing, 2013).

In this chapter, we present a framework for assessing the disruption risk of supply chain network components: facilities (or entities) and transportation links. The assessment is based on a concept that supply chain disruption is influenced not only by the occurrence of risk events but also by the vulnerability of the facilities and transportation links, and risk management practice to cope with the events. The disruption risk assessment can serve as a guideline for practitioners to quantify disruption risks in their supply chains and their financial impacts. This will facilitate the development of risk mitigation strategies and their cost and benefits. The disruption risk assessment is the first module of this research framework, as shown in Figure 3.1.

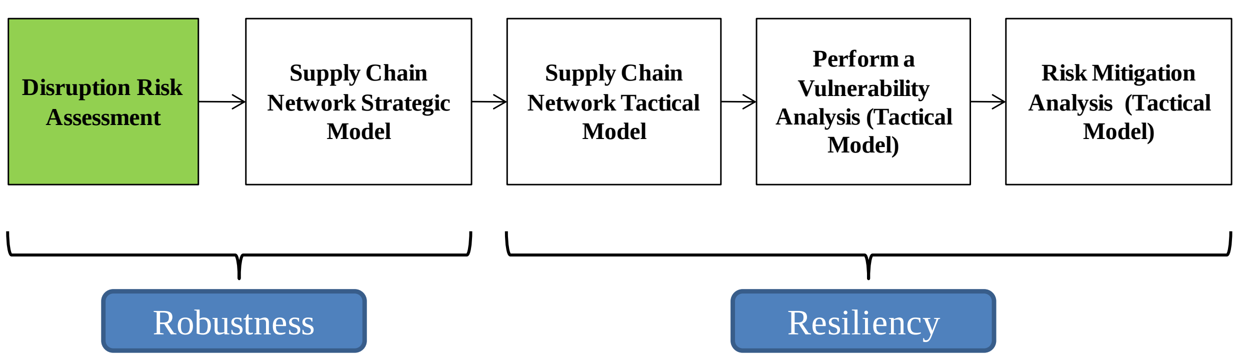


Figure 3.1: Disruption Risk Assessment in a Disruption Risk Management Framework for a Global Supply Chain Network

There are two key terms: *robustness* and *resiliency* that will be used throughout this research. *Robustness* is the ability of a supply chain network to resist risk events or the ability to continue its function in the presence of failures at components or subsystems (Asbjørnslett, 2009; Bundschuh et al., 2003; Klibi and Martel, 2009). *Resilience* is the ability of a supply network to bounce back to a new stable condition after a disruption (Sheffi, 2005; Asbjornlett, 2009; Klibi and Martel, 2009). The focus of these two concepts is different. Robustness focuses on the ability to endure uncertain future events without adapting, whereas resiliency refers to the capability to adapt and survive from a disruption (Asbjornslett, 2009; Husdal, 2008). Husdal (2008) illustrated the difference between these concepts, as shown in Figure 3.2. The thick line represents the supply chain from its current state to a future state. The thin arrows represent future events that may or may not disrupt the supply chain. The thickness of the supply chain arrow indicates the impact of these events to the supply chain.

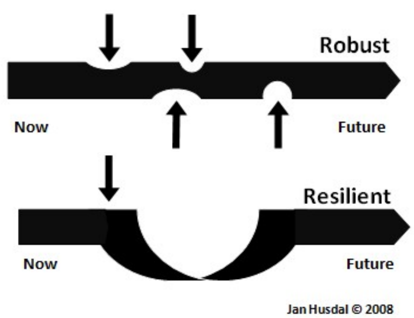


Figure 3.2: Difference between robustness and resiliency from Husdal (2008)

In our research, the disruption risk assessment and the supply chain network strategic model (Chapter 4) are devoted to improve the robustness of a supply chain network. We assess the robustness of a supply chain network based on the hazard, vulnerability, and risk management practice of a supply chain network component. A supply chain network that has facilities and transportation links with low disruption risk should be more robust than a network that has components with high disruption risk. The supply chain network tactical model (Chapter 5) and the vulnerability and the risk mitigation analysis (Chapter 6) are devoted to improve the resiliency of a supply chain network operation. We formulate a mathematical model to support supply chain tactical decisions and evaluate the vulnerability of the supply chain network operations under disruptive scenarios. Then, we apply possible risk mitigation strategies to reduce the negative impacts from possible disruptions.

The remainder of this chapter is organized as follows: Section 3.2 discusses recent supply chain disruptions to point out key factors that influence disruptions of the supply chain. In Section 3.3, we provide an overview of supply chain risk management through the process of risk identification, risk assessment, and risk mitigation, in order to identify research gaps for managing disruption risk in global supply chains. In Section 3.4, we present the disruption risk assessment framework, which is the key contribution of this research. In Section 3.5, we provide examples to illustrate implementation of this framework in assessing and managing disruption risks for facilities and transportation links. In Section 3.6, we discuss the application of the quantified disruption risk value in managing disruption risk in global supply chain. In Section 3.7, we present an actual case study of supplier risk assessment for a global distribution company. Finally, we present conclusions and implications of the proposed disruption risk assessment framework.

3.2 Supply chain disruptions and their key factors

The 2008 airport closure in Thailand is an example of disruption risk in transportation links. Air shipments of hard-disk drives and other electronic products from Thailand were re-routed to airports in Malaysia and Singapore, and trucks were used to transport products out of the country (Nieuwoudt, 2008). This resulted in increased lead-time and transportation cost. The earthquake and tsunami in northeastern Japan and the massive floods in Thailand in 2011 are examples of disruption risks that disrupted both facilities and transportation links. The catastrophe in Japan caused more than 16,000 deaths and cost over 300 billion dollars in property damages and economic loss; many companies had to suspend or shut down production due to parts shortages (Ravindran & Warsing, 2013). The Thailand floods impacted organizations worldwide and forced industries to re-evaluate their global supply chain practices in order to manage disruption risks (Markmann et al., 2012).

Managing supply chains under disruption risks has become a challenge for both practitioners and researchers. In a study by Harvard Business Review Analytic Services (Harvard Business Review, 2011), 89% of companies indicated that natural disasters have been among the top risks over the last three years. From a research perspective, many scholars have attempted to improve supply chain decision-making through risk identification, risk assessment, and risk mitigation. Interested readers are referred to Chapters 7 and 8 in Supply Chain Engineering: Models and Applications by Ravindran and Warsing (2013) for a comprehensive discussion of managing risks in global supply chains.

The airport closure, earthquake, and floods discussed earlier are well-known examples of disruption risks considered to be external risks to supply chain networks (Christopher & Peck, 2004). However, these disruption risks are not the only factors influencing supply chain disruptions. Thailand’s massive floods in 2011 have shown that supply chain disruptions are provoked by a country’s conditions and a lack of effective risk management practices. Geographically, Thailand’s industrial zones are flood-prone, and the country has experienced brief and minor floods from time to time. However, the 2011 monsoon season caused unusually heavy rains in many areas. Poor urban planning, political instability, deforestation, and poor floods mitigation led to an ineffective response to the crisis (Ye & Abe, 2012). Seven industrial estates built on low-lying lands were severely inundated with water, creating profound losses and stopping production at several companies. Even companies whose physical assets were not damaged had to suspend production due to difficulties in obtaining parts from suppliers that had been directly impacted by the floods. The suspensions then spread to other production sites worldwide; Toyota and Honda were forced to halt production in several countries (Fuller, 2011; Ye & Abe, 2012).

Risk management practices, including risk monitoring and risk mitigation, are also important. Although many disruptive risks, such as earthquakes, tsunamis, and floods, are difficult to predict, establishing risk management practices may help to alleviate impacts. During the Thailand floods, many companies underestimated the situation and relied on the government. Water was rising overnight before many plants could move their equipment; the floods damaged infrastructure and equipment and forced the plants to shut down all operations (Fuller, 2011). Another example to illustrate the benefits of risk management practices is the reactions from Ericsson and Nokia to the fire at their supplier, Phillips electronics semi-conductor plant, in New Mexico in March 2000. Nokia responded to the potential disruption quickly by shifting to a backup supplier, and production returned to normal in three weeks (Ravindran & Warsing, 2013). Nokia’s extraordinary efforts and collaborations with its suppliers enabled the company to avoid disrupting its customers (Sheffi, 2005). Ericsson, however, underestimated the situation and had no backup plan. By the time Ericsson realized the magnitude of the problem, it was too late; the company endured parts shortages and lost $640 million in business in the North American mobile phone market (Ravindran & Warsing, 2013; Sheffi, 2005)

For global supply chain networks in which entities are located in different geographical regions and goods are moved through various transportation links, each entity and transportation link has its own disruption risk and vulnerability conditions that may lead to the disruption of the entire supply chain network. Firms must understand both the risks and the vulnerability of their supply chain components when designing the supply chain networks to balance business efficiency and risk (Asbjørnslett, 2009; Craighead et al., 2007; Juttner, 2005; Stecke & Kumar, 2009; Wilson, 2007). In this research, we present an assessment of supply chain risks due to man-made and natural disasters based on *hazard, vulnerability,* and *risk management practice* factors.

3.3 Supply Chain Risk Management

A general framework of supply chain risk management has to include risk identification, risk assessment, and risk mitigation. In this research, we use the risk management process described in Ravindran & Warsing (2013). Interested readers are referred to other studies in Chopra and Sodhi (2004), Handfield and McCormack (2008), Manuj and Mentzer (2008), and Sodhi and Tang (2012).

3.3.1 Risk Identification

Risk identification is defining all potential risks, both internal and external, that organizations may face (Ravindran & Warsing, 2013). The authors classified supply chain risks into financial risks, strategic risks, hazard risks, and operational risks. Our study focuses on natural and man-made disasters, which fall into the hazard risks category. Examples of the hazard risks considered in our study and their importance to supply chain disruptions are given below:

(1) Natural Disasters - Hazard risks due to natural disasters in each country or region may be different. For instance, Asia experiences high economic loss from earthquakes, tsunamis, and

floods. America's economic losses are generally due to storms and hurricanes (Guha-Sapir et al., 2012).

(2) Man-made Disasters - Hazard risks due to man-made disasters, including port closures and piracy, are crucial for global supply chain operations as they impact the transportation flow in the international trade (Loh & Thai, 2011; Rodrigue, 2012). The 2008 airport closure in Thailand caused extra transportation costs and delays. The US West Coast ports' lockout in 2002 lasted for 11 days and cost $11-$22 billion in lost sales, airfreight, and spoilage (Ravindran & Warsing, 2013). The World Economic Forum report (World Economic Forum, 2010) pointed out that disruptions at major ports such as Rotterdam, Hong Kong, or Los Angeles would have significant global impacts. In addition to port closures, piracy is another threat to global supply chains. Chokepoints, such as the Suez Canal, Strait of Malacca, and Strait of Hormuz, are important strategic maritime passages due to the large stream of global freight circulation and economic activities. From a risk perspective, the potential exists for disruption or closure at these points, as they are located near politically unstable countries (Rodrigue, 2012; Ruske & Kauschke, 2012). A report from the International Maritime Bureau indicates the high number of piracy attacks in the South China Sea, East Africa, West Africa, the Indian Ocean, and the Malacca Strait (IMO, 2012). In 2011, there were 439 pirate attacks and 45 merchant vessels hijacked worldwide. More than 50% of these incidents occurred in the Gulf of Aden, of the coast of Somalia, and in the wider Indian Ocean (www.worldshipping.org).

3.3.2 Risk Assessment

Risk assessment is evaluating the impact of disruptions to the supply chain operations (Ravindran & Warsing, 2013). In the supply chain risk management literature, we observe that risk assessment has been done in two domains: risk analysis and vulnerability analysis.

(1) Risk analysis - Risk analysis has been found in most supply chain risk management studies. It focuses on quantifying risks in terms of occurrence and potential impact to a supply chain (Asbjørnslett, 2009). Risk quantification approaches include expert opinion and historical data (Bigun, 1995), game theory (Major, 2002), qualitative assessment by risk rating (Portillo, 2009), risk prioritization using Risk Priority Number (RPN) and risk mapping (Ravindran & Warsing, 2013; Yosha, 2012), occurrence and impact classification (Knemeyer et al., 2009; Stecke & Kumar, 2009), simulation (Vilko & Hallikas, 2012; Wilson, 2007), stochastic model (Goh et al., 2007), Disruption Analysis Network or DA_NET (Wu et al., 2007), Failure Mode and Effect Analysis (FMEA), where the failure is evaluated based on severity, occurrence, and detection (Tuncel & Alpan, 2010), and analytical models (Bilsel, 2009; Yang, 2007).

(2) Vulnerability analysis - Vulnerability analysis is a proactive approach to identify conditions that make supply chains susceptible to risks in order to prepare countermeasures (Asbjørnslett, 2009). Peck (2005) has provided a method for analyzing supply chain vulnerability based on: (i) workflow and information flow, (ii) asset and infrastructure dependencies, (iii) organization and inter-organization networks, and (iv) environmental factors, including the social, political, economic, and natural environments. Craighead et al. (2007) have pointed out that the severity of supply chain disruption depends on two main factors: design characteristics (supply chain density, supply chain complexity, and node criticality) and mitigation capabilities (recovery and warning). Stecke and Kumar (2009) have identified four factors that cause vulnerability: (i) an

increase in the number of exposure points (e.g., transportation routes, transportation modes, geographical factors, socio-economic factors, additional security check points), (ii) increased distance or time, (iii) decreased flexibility due to sole sourcing, and (iv) decreased redundancy through just-in-time or lean policies. Wagner and Neshat (2012) have conducted an empirical study of supply chain vulnerability indices for different categories of firms. We observe that research on supply chain risk assessment that combines both risk analysis and vulnerability analysis was very limited.

3.3.3 Risk Mitigation

Risk mitigation is taking appropriate actions to reduce risks once they are identified and evaluated. General risk mitigation strategies that are suggested in the literature include: (i) taking the risk (e.g., carrying excess inventory), (ii) sharing the risk with partners, (iii) transferring the risk (e.g., making suppliers to assume all the risk), (iv) reducing the risk (e.g., minimizing its impact), (v) eliminating the risk (e.g., redesigning the manufacturing process), and (vi) monitoring the risk (e.g., obtaining real-time data about suppliers' performance) (Chopra & Sodhi, 2004; Handfield & McCormack, 2008; Knemeyer et al., 2009; Ravindran & Warsing, 2013; Sheffi & Rice, 2005; Tomlin, 2006). It is important for companies to evaluate the tradeoff between risk reduction and reward when implementing risk mitigation strategies to ensure that the cost of mitigation does not outweigh the cost of risk (Chopra & Sodhi, 2004).

A review of supply chain risk management literature has revealed two areas for improvement:

(1) Most of the supply chain risk management studies do not assess transportation disruptions explicitly. In a global supply chain, factors that influence facility and transportation disruptions are different. The risks and vulnerability associated with a facility depends on its geographical

location and the conditions in that country, while the risk and vulnerability associated with transportation links depend on the mode of transportation, route, logistics infrastructure, and number of transshipments. Hence, risk assessment for different supply chain components should be performed separately.

(2) Risk assessment in supply chains typically focuses on quantifying the probability of occurrence and the potential economic impact of risks. These two factors are insufficient for understanding the sources of supply chain disruption, especially in a global supply chain, where each supply chain network component has its own risk and vulnerability. Risk assessment should also consider the vulnerability and availability of risk management practices for supply chain components in order to better understand the factors that influence supply chain disruptions and to effectively manage global supply chains under disruption risks.

To fill these research gaps, we propose a disruption risk assessment framework, which is described in the next section.

3.4 Disruption risk assessment framework

The proposed disruption risk assessment framework focuses on assessing the disruption risks due to natural and man-made disasters that may occur at facilities or transportation links. A disruption risk score is determined from a qualitative assessment of three factors: hazard, vulnerability, and risk management practice, and their attributes, as shown in Figure 3.3. We assign each attribute a risk level (1, 2, or 3; higher number indicates higher risk) that a decision maker has to evaluate in order to calculate the factor score and obtain the disruption risk score. Even though other Likert-scales (1 to 5 or 1 to 10) can also be used, we use the three point scale to reduce the cognitive burden of the decision maker. We summarize the disruption risk score calculation as follows:

Step 1: Assess the attributes of each disruption risk factors on a risk level of 1, 2, or 3.

Step 2: Calculate a score value for each factor. The score is a geometric mean of the number of its attributes. It is similar to the Risk Priority Number (RPN) that has been used successfully in auto industries, as well as oil refineries as part of the Failure Mode and Effect Analysis (FMEA) to identify design problems early in the manufacturing process and provide a risk analysis (Breyfogle III, 2003). The concept of RPN is also used in Ravindran & Warsing (2013) and Yosha (2012) to prioritize supply chain risks. Interested readers are referred to the studies from Gargama and Chaturvedi (2011), Su and Chou (2008), and Wang et al. (2009) for the use of geometric mean and RPN in risk evaluation studies.

Step 3: Calculate the disruption risk score for a facility or a transportation link. The disruption risk score is a product of the hazard score, the vulnerability score, and the risk management practice score.

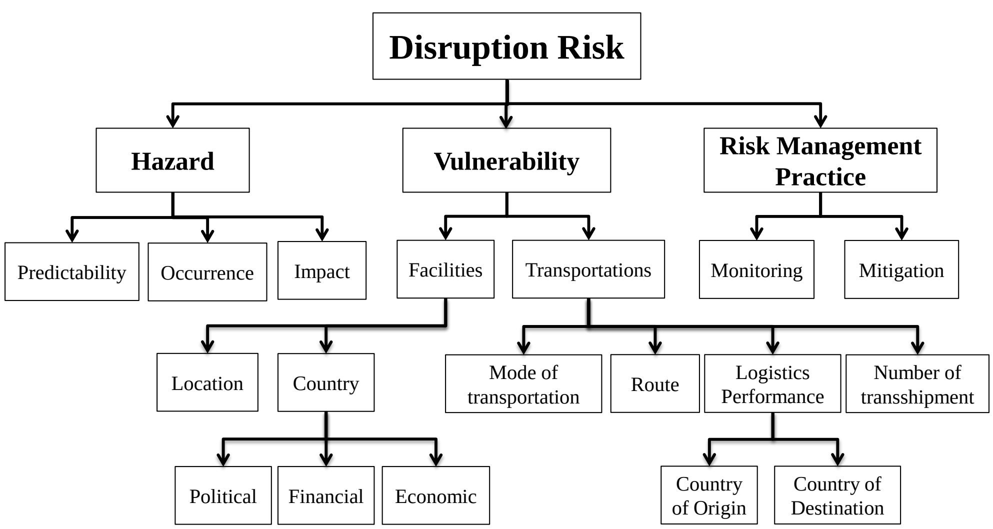


Figure 3.3: Disruption Risk Factors

Following is a guideline for the qualitative assessment of the disruption risk factors' attributes:

(1) Hazard Assessment - Hazard is a possible disruption risk, either man-made (e.g., piracy, port closures) or natural (e.g., earthquakes, floods), that may disrupt a supply chain component. The attributes of a hazard are predictability, occurrence, and impact. The hazard score is the geometric mean of its attributes, which can be determined from Equation (3.1). The risk levels of these attributes are shown in Table 3.1.

$$\text{Hazard score} = (\text{Predictability} \times \text{Occurrence} \times \text{Impact})^{1/3} \tag{3.1}$$

Table 3.1: Hazard Assessment Factor

Predictability	Disruption Risk level	Occurrence	Disruption Risk level	Impact	Disruption Risk level
Unpredictable	3	Yearly	3	Immediately stop operation	3
Somewhat predictable	2	3 years	2	Gradually stop operation (days)	2
Predictable	1	5 years	1	Gradually stop operation (weeks)	1

Predictability: With historical data and advanced technology, some natural disasters are foreseeable, enabling country-specific hazards to be identified. However, it is still difficult to predict when and how those dangerous hazards will occur (Nelson, 2011). If the occurrence of a hazard can be predicted precisely, the risk level is low. Some hazards such as hurricanes and floods are somewhat predictable as they occur seasonally. Some man-made disasters, such as port or airport closures from strikes, are also considered somewhat predictable as they typically result from unsuccessful negotiations between parties; hence, the risk level is medium. Earthquakes and piracy are unpredictable; hence, the risk level is high.

Occurrence: Supply chain network design is a long-term decision. Even though hazards happen infrequently, we may depict risk level based on their occurrences over the entire planning horizon. A company can use historical data, experience, and knowledge to justify this attribute. For instance, the risk level is high if a hazard occurs every year. In contrast, the risk level is low if a hazard occurs infrequently over the planning horizon.

Impact: Hazard impact is usually expressed in monetary terms. However, we consider the impact in terms of the time it takes to disrupt supply chain activities once a hazard occurs. Some hazards, such as earthquakes, develop with little warning and occur rapidly. Such hazards may immediately stop the production and transportation of goods. Hence, risk levels are high. Some hazards, such as floods and port strikes, may take several days to interrupt production and transportation (Nelson, 2011); hence, the risk level is medium. For hazards that take week(s) or longer to disrupt operations, the risk level is low.

(2) Vulnerability Assessment - Vulnerability refers to the exposure of a facility or a transportation link to disruptions. The vulnerability of a facility and a transportation link are evaluated differently due to their distinct roles in the supply chain network. The attributes of a facility's vulnerability are location and the country's political, financial, and economic conditions. The attributes of a transportation link's vulnerability are the mode of transportation, transportation route, logistics performance index (LPI) for both the country of origin and the country of destination, and number of transshipments. The vulnerability scores for a facility and a transportation link are the geometric means of their attributes, which can be determined from Equations (3.2) and (3.3). The risk levels of their attributes are provided in Tables 3.2 and 3.3.

Vulnerability of a Facility

$$\text{Vulnerability score of facility} = (\text{Location} \times \text{Political} \times \text{Financial} \times \text{Economic})^{1/4} \quad (3.2)$$

Table 3.2: Vulnerability Assessment Factor for Facilities

Location of facility to the vulnerable area(s)	Disruption Risk level	Political Instability	Disruption Risk level	Financial Instability	Disruption Risk level	Economic Instability	Disruption Risk level
Close	3	High	3	High	3	High	3
Far	2	Medium	2	Medium	2	Medium	2
Not in effected area	1	Low	1	Low	1	Low	1

Location: The risk level of a facility is high if its location is much closer to a vulnerable area, and the risk level of a facility is lower if its location is farther from a vulnerable area. The location could also refer to a supplier's location, which also may be vulnerable to disruption risks.

Political: Political conditions in a country have implication to supply chain disruptions, as seen during the massive floods in Thailand. Disasters may be less severe in countries with efficient, transparent, and accountable governments because they engage in both pre-disaster planning and post-disaster recovery planning, making them able to respond to natural disasters better than corrupt governments (Kellenberg & Mobarak, 2008; Stromberg, 2007; Ye & Abe, 2012). Political instability has been considered as a factor when making supply chain strategic decisions, such as supplier selection and supply chain network design (Banhan, 2011; Portillo, 2009). In this framework, the risk level is high if a country has high political instability.

Financial: Financial situation of a country or a region (e.g., credit, inflation, currency, foreign debt, and cross-border trade) impacts supply chains in several ways. From Ferrari (2011), a weakened banking sector could cause credit crisis and hence impact corporate working capital, production, and inventory strategies. A currency breakdown may affect supplier contracts and invoices for international suppliers and customers. Logistics and customs requirements could be impacted if certain countries change their customs duty and transport regulations. A financial crisis could potentially increase import tariff. In our disruption risk assessment framework, the risk level is high if a country has high financial instability.

Economic: Economic condition of a country represents its strength and weakness based on gross domestic product (GDP) per capita (The PRS Group, 2011). Studies from Kahn (2005), Kellenberg and Mobarak (2008), and Gaiha et al. (2010) have concluded that GDP per capita is related to damage from disruptive events. The authors state that countries in which citizens have low incomes are more vulnerable to disasters than countries in which citizens have higher incomes. Efforts to mitigate the impact of disaster risks in developing countries are less than in developed countries; developing countries often under-invest in protection, whereas developed countries may lower their exposure to disaster risks by improving the quality of institutions, educations, or access to medical care. FM Global (2011) points out that a developing country like China is a major exporter and importer of goods and hence highly connected to the world economy. If economic instability or disaster occurs in China, which has not yet fully implemented risk management practices, the negative impacts to global supply chains could be far reaching and longer than the one that happened in Japan. For our assessment, the value of risk level is high if a country has high economic instability or is highly connected to the world economy.

Vulnerability of a Transportation Link

$$\text{Vulnerability score of transportation link} = (\text{Mode}\times\text{Route}\times LPI_O\times LPI_D\times\text{Number of transshipment})^{1/5} \tag{3.3}$$

Table 3.3: Vulnerability Assessment Factors for Transportation Links

Mode of transportation	Disruption Risk level	Route	Disruption Risk level	Logistics Performance Index	Disruption Risk level	Number of transshipment	Disruption Risk level
Ship	3	Multiple countries	3	Poor	3	High	3
Airplane	2	Few countries	2	Good	2	Medium	2
Truck	1	Domestic	1	Very good	1	Low	1

Mode of Transportation: Different modes of transportation contribute to different levels of disruption risk to the transportation link. However, it depends on which aspect of transportation mode is considered when assigning the risk level (e.g., travel time, capacity, vulnerability, etc.). We assign the highest risk level to ships, followed by airplanes and trucks, respectively. This is because ships require the longest travel time, making them highly exposed to disruptions.

Airplanes are assigned a higher risk value than trucks due to higher capacity and vulnerability to attacks.

Route: Transportation routes for a global supply chain play an important role in disruptions. Aspects to consider for routes may include: the number of countries a particular shipment is passing through, regional characteristics, gateways, chokepoints, and geographic features such as canals or straits. For instance, Singapore is one of the busiest intermediate hubs that accounts for 85% of the total cargo traffic to other regions and thus could be a more likely target for airport closures (Ruske & Kauschke, 2012). Geographic features such as bridges or canals (e.g., Suez Canal, Strait of Malacca) must be considered when shipping internationally; capacity and landscape constraints make bypassing them a difficult option, and the area is prone to piracy (Ruske & Kauschke, 2012). Increasing security measures to the chokepoint to prevent piracy will result in additional transportation costs and time. Re-routing, using alternate route, would imply significant financial costs and delays (Ruske & Kauschke, 2012). Hence, the risk level is high if a route travels through multiple countries or connects to an important logistics hub or chokepoint. The risk level is lower for a route traveling through fewer countries or domestically.

Logistics Performance Index (LPI): The LPI indicates the overall quality and readiness of the logistics infrastructure of each country. It includes efficiency of the customs clearance process, quality of trade and transport related infrastructure, ease of arranging competitively priced international shipments, logistics competence of transport operations, customs brokers, tracking and tracing of consignments, and timeliness of shipments in reaching destinations (The World Bank, 2012). The risk level is high if the LPI value is low. In our calculation, we consider the LPI of the country of origin (LPI_O) and the country of destination (LPI_D) separately.

Number of Transshipments: This factor refers to the handling of goods during transfers between carriers or for inspection purposes throughout a transportation process. Higher number of transshipment activities results in more chances of disruptions due to mishandling, pilferage, spoilage, etc. After the 9/11 attacks, transportation security has become a necessary consideration for global supply chains. Security inspection times for inbound containers to the United States have increased significantly (Banomyong, 2005). Hence, the risk level is high if the number of transshipments is large.

(3) Risk Management Practice - Risk management practice can be evaluated based on the existence of risk monitoring and risk mitigation activities. The risk management score is a geometric mean of its attributes as shown in Equation (3.4). The risk levels of the two attributes are presented in Table 3.4.

$$\text{Risk management practice score} = (\text{Monitoring} \times \text{Mitigation})^{1/2} \tag{3.4}$$

Table 3.4: Risk Management Practice Assessment Factors

Risk Monitoring	Disruption Risk level	Risk Mitigation	Disruption Risk level
Not available	3	Not available	3
Preparation	2	Preparation	2
Available	1	Available	1

Risk Monitoring: Risk monitoring activities include supplier coordination strategies, monitoring systems, and international standards. They can be used to monitor risks that could disrupt supply chain operations. The risk level is the highest if no risk monitoring practices exist, and lower if the risk monitoring practices are being prepared or already exist.

Risk Mitigation: Risk mitigation strategies include backup suppliers, backup transportation links, flexible capacity, inventory, etc. Risk mitigation ensures the continuity of supply chain operations when disruptions occur. The risk level is the highest if no risk mitigation strategies exist, and lower if risk mitigation strategies are being prepared or already exist.

Once the hazard, vulnerability, and risk management practice scores are estimated, the disruption risk score for each facility and transportation link is calculated using Equation (3.5).

$$\text{Disruption risk score} = \text{Hazard score} \times \text{Vulnerability score} \times \text{Risk management practice score} \quad (3.5)$$

3.5 Illustrative Examples

This section provides two examples of the disruption risk score calculations based on the proposed disruption risk assessment framework. Example 1 presents a disruption risk assessment for suppliers and Example 2 presents a disruption risk assessment for the transportation links between plants and distribution centers (DCs).

Example 1: Disruption Risk Assessment for Suppliers

Suppose there are three suppliers, S1, S2, and S3, which are located in Japan, Thailand, and China. Based on a manager’s experience and information from the Natural Disaster Hotspots and Vulnerable Countries report issued by World Bank (The World Bank, 2005), these three countries are prone to different natural disasters. Supplier S1 is prone to earthquake, which is unpredictable and occurs frequently, potentially causing a sudden disruption in the supplier’s operations. Suppliers S2 and S3 are prone to floods during the monsoon season. Floods are more predictable and may take few days to impact the suppliers’ operations. Using the guidelines from Table 3.1, the manager assesses the predictability, occurrence, and impacts of hazards for suppliers S1, S2, and S3, as shown in Table 3.5. Using Equation (3.1), the hazard score for suppliers S1, S2, and S3 are 3.000, 2.289, and 2.289, respectively.

Table 3.5: Hazard Scores for Suppliers

Supplier	Hazard			Hazard Score
	Predictability	Occurrence	Impact	
S1 (Japan)	3	3	3	3.000
S2 (Thailand)	2	3	2	2.289
S3 (China)	2	3	2	2.289

Next, the manager evaluates vulnerability of these suppliers. Supplier S1's facility is located near a coastal area; hence, it is considered to be high risk. Supplier S2 is located in an area that is prone to flooding. However, with heavy rains, it may take a few days for the area to be flooded. Supplier S3 is located in a city with a good drainage system. The manager assigns a risk level of 3, 3, and 2 for suppliers S1, S2, and S3. To determine the risk associated with the country where a supplier is located, the manager refers to a 5-year forecast for worst-case scenario from the International Country Risk Guide (ICRG) published by the PRS Group. The vulnerability assessment and vulnerability scores are summarized in Table 3.6.

Table 3.6: Vulnerability Scores for Suppliers

Supplier	Vulnerability				Vulnerability Score
	Location	Political Instability	Financial Instability	Economic Instability	
S1 (Japan)	3	1	2	3	2.060
S2 (Thailand)	3	2	2	3	2.449
S3 (China)	2	2	2	3	2.213

The manager has visited all three suppliers to evaluate their risk management practices. Supplier S1 has implemented an international standard and a warning system; suppliers S2 and S3 have not yet established any risk monitoring programs. Hence, the risk levels for these suppliers are 1, 3, and 3 for risk monitoring. Supplier S1 is preparing a mitigation plan to manage disruption risk, whereas suppliers S2 and S3 have not yet established risk mitigation strategies.

Hence, the risk levels for these suppliers are 2, 3, and 3 for risk mitigation. The risk management scores of these suppliers are summarized in Table 3.7.

Table 3.7: Risk Management Practice Scores for Suppliers

Supplier	Risk Management Practice		Risk Management Practice Score
	Monitoring	Mitigation	
S1 (Japan)	1	2	1.414
S2 (Thailand)	3	3	3.000
S3 (China)	3	3	3.000

Using Equation (3.5), the disruption risk score of supplier S1 is (3.000 x 2.060 x 1.414) = 8.739. The disruption risk scores of suppliers S2 and S3 are 16.817 and 15.196, as shown in Table 3.8.

Table 3.8: Disruption Risk Scores for Suppliers

Supplier	Hazard Score	Vulnerability Score	Risk Management Practice Score	Disruption Score
S1 (Japan)	3.000	2.060	1.414	**8.739**
S2 (Thailand)	2.289	2.449	3.000	**16.817**
S3 (China)	2.289	2.213	3.000	**15.196**

Example 2: Disruption Risk Assessment for Transportation Links between Plants and DCs

Suppose the manager wants to evaluate the disruption risk for the transportation links between plants (M1 and M2), which are located in Thailand and Malaysia, and DCs (N1 and N2), which are located in the United States. There are two transportation links, U1 (air) and U2 (ship), available between the plants and the DCs, as listed in Column 1 of Table 3.9. Airport closures from strikes are hazards for air transportation, while piracy is a hazard for maritime transportation. The manager evaluates that airport closures are somewhat predictable and may take some time to stop transportation, whereas piracy is unpredictable and may stop transportation immediately. Both hazards do not occur frequently. The hazard assessment and hazard scores of the transportation links are presented in Table 3.9.

Table 3.9: Hazard Scores for Transportation Links between Plants and DCs

Transportation	Hazard			Hazard Score
	Predictability	Occurrence	Impact	
U1_M1N1(Air)	2	1	2	1.587
U1_M1N2(Air)	2	1	2	1.587
U1_M2N1(Air)	2	1	2	1.587
U1_M2N2(Air)	2	1	2	1.587
U2_M1N1(Ship)	3	1	3	2.080
U2_M1N2(Ship)	3	1	3	2.080
U2_M2N1(Ship)	3	1	3	2.080
U2_M2N2(Ship)	3	1	3	2.080

For vulnerability, the manager assigns a medium risk level for the U1 routes and a high risk level for the U2 routes. The logistics performance index (LPI) is based on a 1 to 5 scale, where 1 indicates the worst performance and 5 indicates the best performance. The LPIs of Thailand, Malaysia, and the United States are 3.18, 3.49, 3.93, respectively (The World Bank, 2012). Suppose the manager assigns a risk level for the LPI as follows:

LPI range 1.00 – 2.50 indicates high risk level,

LPI range 2.51 – 3.75 indicates medium risk level, and

LPI range 3.76 – 5.00 indicates low risk level

Hence, the LPI risk levels are 2 for the countries where the plants are located, and the risk levels are 1 for the country where the DCs are located. Next, the manager assigns risk levels for mode of transportation using the guideline in Table 3.3. The manager rates the number of transshipments as high risk due to handling between carriers and security checks. The vulnerability assessment and vulnerability scores of links between plants and DCs are summarized in Table 3.10.

Table 3.10: Vulnerability Scores for Transportation Links between Plants and DCs

Transportation	Vulnerability					Vulnerability Score
	Mode of Transportation	Route	LPI_O	LPI_D	No. of Transshipment	
U1_M1N1(Air)	2	2	2	1	3	1.888
U1_M1N2(Air)	2	2	2	1	3	1.888
U1_M2N1(Air)	2	2	2	1	3	1.888
U1_M2N2(Air)	2	2	2	1	3	1.888
U2_M1N1(Ship)	3	3	2	1	3	2.221
U2_M1N2(Ship)	3	3	2	1	3	2.221
U2_M2N1(Ship)	3	3	2	1	3	2.221
U2_M2N2(Ship)	3	3	2	1	3	2.221

Suppose risk monitoring and risk mitigations are in preparation for all the transportation links. The manager then assigns a risk level of 2 for all of them. The risk management practice assessment and risk management practice scores for links between the plants and DCs are summarized in Table 3.11.

Table 3.11: Risk Management Practice Scores for Transportation Links between Plants and DCs

Transportation	Risk Management Practice		Risk Management Practice Score
	Monitoring	Mitigation	
U1_M1N1(Air)	2	2	2.000
U1_M1N2(Air)	2	2	2.000
U1_M2N1(Air)	2	2	2.000
U1_M2N2(Air)	2	2	2.000
U2_M1N1(Ship)	2	2	2.000
U2_M1N2(Ship)	2	2	2.000
U2_M2N1(Ship)	2	2	2.000
U2_M2N2(Ship)	2	2	2.000

Using Equation (3.5), the disruption risk scores for the transportation links between the plants and DCs are calculated as shown Table 3.12.

Table 3.12: Disruption Risk Scores for Transportation Links between Plants and DCs

Transportation	Hazard Score	Vulnerability Score	Risk Management Practice Score	Disruption Risk Score
U1_M1N1(Air)	1.587	1.888	2.000	**5.995**
U1_M1N2(Air)	1.587	1.888	2.000	**5.995**
U1_M2N1(Air)	1.587	1.888	2.000	**5.995**
U1_M2N2(Air)	1.587	1.888	2.000	**5.995**
U2_M1N1(Ship)	2.080	2.221	2.000	**9.238**
U2_M1N2(Ship)	2.080	2.221	2.000	**9.238**
U2_M2N1(Ship)	2.080	2.221	2.000	**9.238**
U2_M2N2(Ship)	2.080	2.221	2.000	**9.238**

The disruption risk scores from Example 1 (Table 3.8) show that supplier S2 has the highest disruption risk, followed by suppliers S3 and S1, respectively. The disruption risk scores from Example 2 (Table 3.12) show that all transportation links between the plants and DCs that use mode U2 (ship) have higher disruption risks than the links that use mode U1 (air).

3.6 Application of Disruption Risk Scores

Disruption Risk Matrix

Disruption risk matrix is a quick way to visualize the relative risk of all identified hazards. This technique has been widely used in supply chain risk management to identify, prioritize, and establish a risk profile (Norrman & Jansson, 2004; Ravindran & Warsing, 2013; Yosha, 2012). Companies can develop a disruption risk matrix by locating the quantified hazard scores, vulnerability scores, and risk management practices score of all facilities and transportation links as an x-y plot.

A disruption risk matrix (2x2) is constructed as follows:

- The x-axis represents the quantified hazard score on a scale from 1 to 3;
- The y-axis represents the quantified vulnerability score on a scale from 1 to 3; and
- A triangle, circle, and square is used to represent the quantified risk management practice score.
    - A triangle represents the nonexistence of risk monitoring or risk mitigation practices (the risk management practice score is 2.000-3.000)
    - A circle represents the existence of the risk monitoring or risk mitigation practices (the risk management practice score is 1.001-1.999)

- A square represents the existence of both risk monitoring and risk mitigation practices (the risk management practice score is 1.000)

In this way, each facility and each transportation link connecting two facilities can be represented on the risk matrix. An illustrative example is given in Figure 3.4.

Interpretation of the risk matrix - The risk matrix is divided into four disruption zones as follows:

- Zone I: A facility (or a transportation link) has a critical disruption risk due to both hazard and vulnerability
- Zone II: A facility (or a transportation link) has a high disruption risk due to vulnerability
- Zone III: A facility (or a transportation link) has a high disruption risk due to hazard
- Zone IV: A facility (or a transportation link) has a low disruption risk

Facilities (or transportation links) that fall into Zone I should be of primary concern for a company, followed by those in zones II, III, and IV, respectively. A disruption risk profile helps a company to have a better understanding of their supply chain components from a disruption risk perspective, such that appropriate risk mitigation strategies can be developed to prevent supply chain disruptions.

Using Example 1 (Tables 3.5 and 3.6), we create a disruption risk matrix for suppliers S1, S2, and S3, as shown in Figure 3.4. Since all three suppliers fall into Zone I, a company needs to take appropriate actions to prevent disruptions to the supply chain. Using the risk management practice scores (Table 3.8), supplier S1 is represented by a circle, while S2 and S3 are represented by triangles. For supplier S1, a company may collaborate with the supplier to obtain real-time risk monitoring information, or carry excess inventory to reduce the risk impact. For suppliers S2 and S3, with high vulnerability and risk management practice scores, the company should proactively develop risk mitigation plans and closely monitor these suppliers.

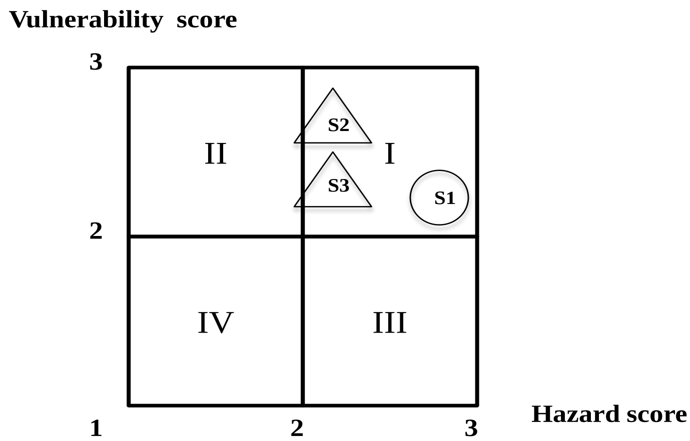


Figure 3.4: Disruption Risk Matrix of Suppliers

3.7 Case Study: Disruption Risk Assessment of Suppliers

This section illustrates how to apply the proposed disruption risk assessment framework (described in Section 3.4) to quantify the disruption risk of suppliers. We have obtained data from a global distribution company that wants to evaluate the disruption risk of 20 international suppliers, who are located in the Asia Pacific region. Products are shipped from the suppliers to two distribution centers in the United States. To facilitate the risk assessment, we created a risk assessment spreadsheet (see Appendix 3A) with instructions to the company. The assessment has been completed by the global sourcing team of the company. From the data we have received, there are two suppliers with no risk event identified. Four suppliers have been identified with more than one disruptive event. We treat each disruptive event separately.

Due to the confidentiality of the data, we do not disclose information related to the company. Throughout this case study, we use letters S to represent suppliers (e.g., S1 denotes supplier 1), L for transportation link between supplier to destination (e.g., L1 denotes a transportation link from supplier S1). From the data provided by the company, we first summarize key observations about suppliers' locations, risk events and availability of risk management practices to cope with the risk events, transportation links between suppliers to destinations, risk events to the transportation links and availability of risk management practices to cope with the risk events. Finally, we summarize the disruption risk scores of facilities and transportation links.

3.7.1 Locations of International Suppliers

Out of the 20 international suppliers the company uses, 10 suppliers are in China, 3 are in India, 2 are in Malaysia and one each from Hong Kong, Indonesia, Taiwan, Thailand, and South Korea. From Figure 3.5, supplier locations are identified by circles; for suppliers that are located in China, majority of them are located on the East Coast and South East areas.

Figure 3.5: Locations of suppliers (map is adapted from www.wetcatasia.com)

3.7.2 Risk Events to Facilities

From 20 suppliers, 2 suppliers do not have risk event identified (suppliers S10 and S20). In addition, 4 suppliers have more than one risk event identified (suppliers S1, S2, S18, and S19). Table 3.13 summarizes the risk events of all suppliers.

Table 3.13: Risk events (or hazards) from suppliers

Hazard	Count	Percentage
Unstable workforce	5 (3 of 5 are from China)	21.74%
Unstable capacity	3	13.04%
Minimum order quantity	3	13.04%
Poor working condition	2	8.80%
Short product life cycle	2	8.80%
Equipment breakdown	2	8.80%
Lack of manufacturing control	2	8.80%
FDA alert	2	8.80%
Imported raw material supplies	1	4.35
Flood	1	4.35%
Total	**23**	**100%**

Note that, for suppliers in China and Hong Kong, the top two risk events are unstable workforce and lack of manufacturing control. All the suppliers in India have minimum order quantity issue, while suppliers in Malaysia have issues related to Food & Drug Administration (FDA) alert, production capacity, and minimum order quantity.

3.7.3 Risk Management Practice

From the 18 suppliers that the company has identified the risk events, 4 suppliers (S1, S2, S18, and S19) have more than one hazard identified. In total, there are 23 identified hazards. Based on the company’s assessment, 18 out of the 23 hazards (or 78.26%) do not have any risk monitoring in place, 2 hazards have risk monitoring in preparation, and 3 hazards have risk monitoring in place, as shown in Table 3.14.

Table 3.14: Risk Control (for facility hazards)

Risk Monitoring Availability	Count	Percentage
Available	3	13.04%
In preparation	2	8.80%
Not available	18	78.26
Total	**23**	**100%**

In terms of risk mitigation, 17 hazards (or 73.91%) do not have risk mitigations in place, 3 hazards have risk mitigation in place, and 3 are in preparation, as shown in Table 3.15.

Table 3.15: Risk Mitigation (for facility hazards)

Risk Mitigation Availability	Count	Percentage
Available	3	13.04%
In preparation	3	13.04%
Not available	17	73.91%
Total	**23**	**100%**

It is important to note that risk management practice assessment is to check the availability of risk control and risk mitigation. The assessment does not evaluate the effectiveness of those risk management practices.

3.7.4 Transportation Mode

By considering transportation modes used from suppliers in the Asia Pacific region to destinations in the United States, 19 out of 20 links are operated by ship (95%) and one by air (5%).

Table 3.16: Transportation Mode

Transportation Mode	# of links	Percentage
Truck only	0	0.00%
Air	1	5.00%
Ship	19	95.00%
Total	**20**	**100%**

3.7.5 Risk Events in the Transportation Network Identified by the Company

For the 19 transportation links, the company has identified 6 different hazards. Some links have more than one hazard identified. From Table 3.17, the top three hazards, which account for 74.21%, are from feeder vessel delay, weather, and strike.

Table 3.17: Hazards on Transportation Link

Hazard	Count	Percentage	Routes
Feeder vessel delay	8	25.81%	India – USA, China – USA,
			HK – USA, Thailand - USA
Weather conditions	8	25.81%	China – USA, HK – USA
Strike	7	22.59%	India – USA, Malaysia – USA,
			China – USA, Korea - USA
Port closure	3	9.67%	South Korea, Malaysia - USA
Port congestion	3	9.67%	India - USA
Vessel space	2	6.45%	China - USA
Total	**31**	**100%**	

- **Weather, feeder vessel delay, vessel space, and strike** are the hazards at transportation between suppliers in **China** to destinations in **the United States**.
- **Feeder vessel delay, port congestions, and strike** are the hazards at transportation links between suppliers in **India** to destinations in **the United States**.
- **Port closure, strike, and feeder vessel delay** are the main hazards at transportation links between suppliers in **Malaysia t**o destinations in **the United States**.

3.7.6 Risk Management Practice on the Transportation Network

In terms of risk monitoring for the transportation network, 23 of the 31 hazards (or 74.19%) do not have any risk monitoring in place and 8 hazards (or 25.81%) have risk monitoring in preparation only. None of the risk event has risk monitoring in place. The results are shown in Table 3.18.

Table 3.18: Risk monitoring (for hazards on transportation link)

Risk Monitoring Availability	Count	Percentage
Available	0	0.00%
In preparation	8	25.81%
Not available	23	74.19%
Total	**31**	**100%**

For risk mitigation for the transportation network, 23 of 31 hazards (or 74.19%) do not have any risk mitigation in place and 8 hazards (or 25.81%) have risk mitigations in preparation. None of the risk event has risk mitigation in place. The results are shown in Table 3.19.

Table 3.19: Risk mitigation (for hazards on transportation link)

Risk Mitigation Availability	Count	Percentage
Available	0	0.00%
In preparation	8	25.81%
Not available	23	74.19%
Total	**31**	**100%**

3.7.7 Disruption Risk Score of Facilities

For the 18 suppliers that the company has identified the risk events and for the 4 suppliers that have more than one risk, there are 23 disruption risk scores. The disruption risk scores are summarized from the highest score to the lowest as shown in Table 3.20. Note that suppliers S10 and S20, which are located in China, have no risk event identified.

Table 3.20: Suppliers' Disruption Risk Scores

No.	Supplier	Country	Possible Risk Events	Hazard Score	Vulnerability Score	Risk Management Practice Score	Disruption Risk Score
1	S1	China	Equipment breakdown	2.6207	2.7108	3.0000	21.3130
2	S1	China	Poor working condition	2.6207	2.7108	3.0000	21.3130
3	S13	Indonesia	FDA Alert	2.0801	3.0000	3.0000	18.7208
4	S17	India	Minimum order quantity	2.0801	3.0000	3.0000	18.7208
5	S18	India	Minimum order quantity	2.0801	3.0000	3.0000	18.7208
6	S2	China	Short Product Life Cycle	2.2894	2.7108	3.0000	18.6186
7	S4	China	Lack of manufacturing control	2.2894	2.7108	3.0000	18.6186
8	S14	China	Unstable workforce	2.0801	2.7108	3.0000	16.9161
9	S19	China	Unstable workforce	2.0801	2.7108	3.0000	16.9161
10	S19	China	Seasonal power outage	1.8171	2.7108	3.0000	14.7776
11	S16	Thailand	Flood	2.2894	2.0598	3.0000	14.1471
12	S1	China	Unstable workforce	2.0801	2.7108	2.4495	13.8119
13	S15	India	Minimum order quantity	1.4422	3.0000	3.0000	12.9802
14	S8	Malaysia	FDA Alert	2.0801	2.0598	3.0000	12.8535
15	S2	China	Unstable capacity	2.0801	2.7108	2.0000	11.2774
16	S9	Taiwan	Unstable workforce	2.0801	1.7321	3.0000	10.8084
17	S7	Korea	Short Product Life Cycle	2.2894	1.5651	3.0000	10.7494
18	S5	Malaysia	Minimum order quantity	2.0000	1.5651	3.0000	9.3905
19	S18	India	Imported Raw material supplies	1.8171	2.2795	2.0000	8.2843
20	S12	Hong Kong	Unstable workforce	2.0801	1.3161	3.0000	8.2126
21	S3	China	Lack of manufacturing control	2.2894	2.7108	1.0000	6.2062
22	S6	China	Seasonal temperature/humidity impact	1.8171	2.7108	1.0000	4.9259
23	S11	China	Minimum order quantity	1.0000	2.7108	1.0000	2.7108

Using the disruption risk score in Table 3.20, the company can identify their suppliers' disruption risk level. For example, supplier S1 is the highest risk supplier with the disruption risk score of 21.3130. Risk events associated with supplier S1 are equipment breakdown and poor working condition. The company should work with the supplier to establish appropriate actions. Supplier S9 is the medium risk supplier with the disruption risk score of 10.8084. A risk event associated with supplier S9 is unstable workforce, which typically occurs during long holidays.

The company may adjust the forecasting or increase the inventory to mitigate the risk during the holiday seasons. Supplier S11 is the lowest risk supplier with the disruption risk score of 2.7108. A risk event associated with supplier S11 is the order quantity issue. Even though the disruption risk score of supplier S11 is low, the company may need to evaluate the effectiveness of the risk management practices. Finally, the company can use the facilities' disruption risk scores to create a disruption risk matrix for the suppliers' facilities, as shown in Figure 3.6.

Disruption Risk Matrix (Facilities)

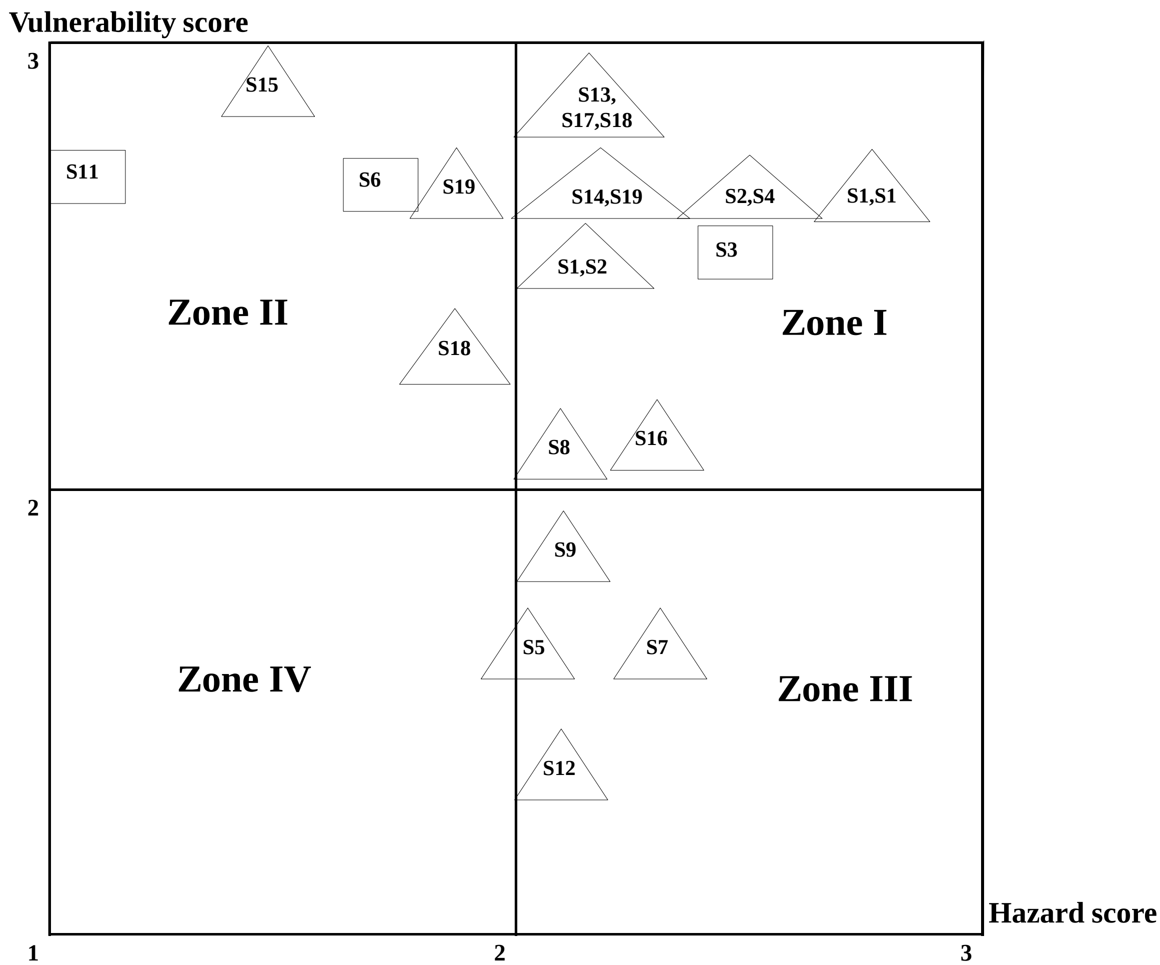


Figure 3.6: Disruption risk profile of suppliers

From disruption risk matrix of suppliers' facilities, we observe the following:

- Out of the 23 risk events of the 18 suppliers, 14 events from 11 suppliers (S1, S2, S3, S4, S8, S13, S14, S16, S17, S18, and S19) are in the critical disruption zone (Zone I). From these, 12 events do not have any risk management practice available. Hence, the company should focus on managing disruption risk of these suppliers.
- There are 5 events from 5 suppliers (S6, S11, S15, S18, and S19) that fall in Zone II. From these, 3 events do not have any risk management practice in place. Company may encourage the suppliers to establish corrective actions for those risk events to lower their disruption risk scores.
- There are 4 events from 4 suppliers (S5, S7, S9, and S12) in Zone III, which has the high hazard score. All of these events do not have any risk management practice in place. Two events are related to the unstable workforce, which typically occurs during the Chinese New Year. The company may adjust the forecasting or inventory level to reduce the impacts of these risk events.

3.7.8 Disruption Score of Transportation Link

From the 20 transportation links (from 20 suppliers), there are 2 transportation links that the company has not identified risk events (L6 and L20). Out of the 18 transportation links, 9 links have more than one risk event identified; hence, there are 31 disruption risk scores. The disruption risk scores are summarized from the highest to the lowest, as shown in Table 3.21. Using the disruption risk score in Table 3.21, the company can identify the disruption risk level to the transportation links. For example, the transportation link L12 has the highest disruption risk (disruption risk score of 17.4592), while the transportation link L9 has the lowest disruption risk (disruption risk score of 6.4784).

Table 3.21: Transportation links' disruption risk scores

No.	Transportation link	Country of Origin - Country of Destination	Possible Risk Events	Hazard Score	Vulnerability Score	Risk Management Practice Score	Disruption Risk Score
1	L12	China - USA	Weather	2.6207	2.2206	3.0000	17.4592
2	L12	China - USA	Strike	2.6207	2.2206	3.0000	17.4592
3	L1	China - USA	Feeder Vessel delay	2.0801	2.2206	3.0000	13.8574
4	L1	China - USA	Mother Vessel tight space	2.0801	2.2206	3.0000	13.8574
5	L15	India - USA	Feeder Vessel delay	2.0801	2.2206	3.0000	13.8574
6	L15	India - USA	Port congestion	2.0801	2.2206	3.0000	13.8574
7	L15	India - USA	Strikes	2.0801	2.2206	3.0000	13.8574
8	L17	India - USA	Feeder Vessel delay	2.0801	2.2206	3.0000	13.8574
9	L17	India - USA	Port congestion	2.0801	2.2206	3.0000	13.8574
10	L17	India - USA	Strikes	2.0801	2.2206	3.0000	13.8574
11	L18	India - USA	Feeder Vessel delay	2.0801	2.2206	3.0000	13.8574
12	L18	India - USA	Port congestion	2.0801	2.2206	3.0000	13.8574
13	L18	India - USA	Strikes	2.0801	2.2206	3.0000	13.8574
14	L19	China - USA	Feeder Vessel delay	2.0801	2.2206	3.0000	13.8574
15	L19	China - USA	Mother Vessel tight space	2.0801	2.2206	3.0000	13.8574
16	L16	Thailand - USA	Feeder Vessle delay	1.8171	2.2206	3.0000	12.1055
17	L2	China - USA	Weather	1.4422	2.2206	3.0000	9.6082
18	L3	China - USA	Weather	1.4422	2.2206	3.0000	9.6082
19	L4	China - USA	Weather	1.4422	2.2206	3.0000	9.6082
20	L5	Malaysia - USA	Feeder Vessle delay	1.4422	2.2206	3.0000	9.6082
21	L10	China - USA	Weather	1.4422	2.2206	3.0000	9.6082
22	L11	China - USA	Weather	1.4422	2.2206	3.0000	9.6082
23	L14	China - USA	Weather	1.4422	2.2206	3.0000	9.6082
24	L7	Korea - USA	Port closure	1.8171	2.2206	2.0000	8.0704
25	L7	Korea - USA	Strike in Seattle	1.8171	2.2206	2.0000	8.0704
26	L8	Malaysia - USA	Port closure	1.8171	2.2206	2.0000	8.0704
27	L8	Malaysia - USA	Strike in Seattle	1.8171	2.2206	2.0000	8.0704
28	L13	Malaysia - USA	Port closure	1.8171	2.2206	2.0000	8.0704
29	L13	Malaysia - USA	Strike in Seattle	1.8171	2.2206	2.0000	8.0704
30	L9	Hong Hong - USA	Weather	1.8171	1.7826	2.0000	6.4784
31	L9	Hong Hong - USA	Feeder Vessel delay	1.8171	1.7826	2.0000	6.4784

Using the transportation links' disruption risk scores, the company can also create the disruption risk matrix of the transportation links from the suppliers, as shown in Figure 3.7.

Disruption Risk Matrix (Transportation Links)

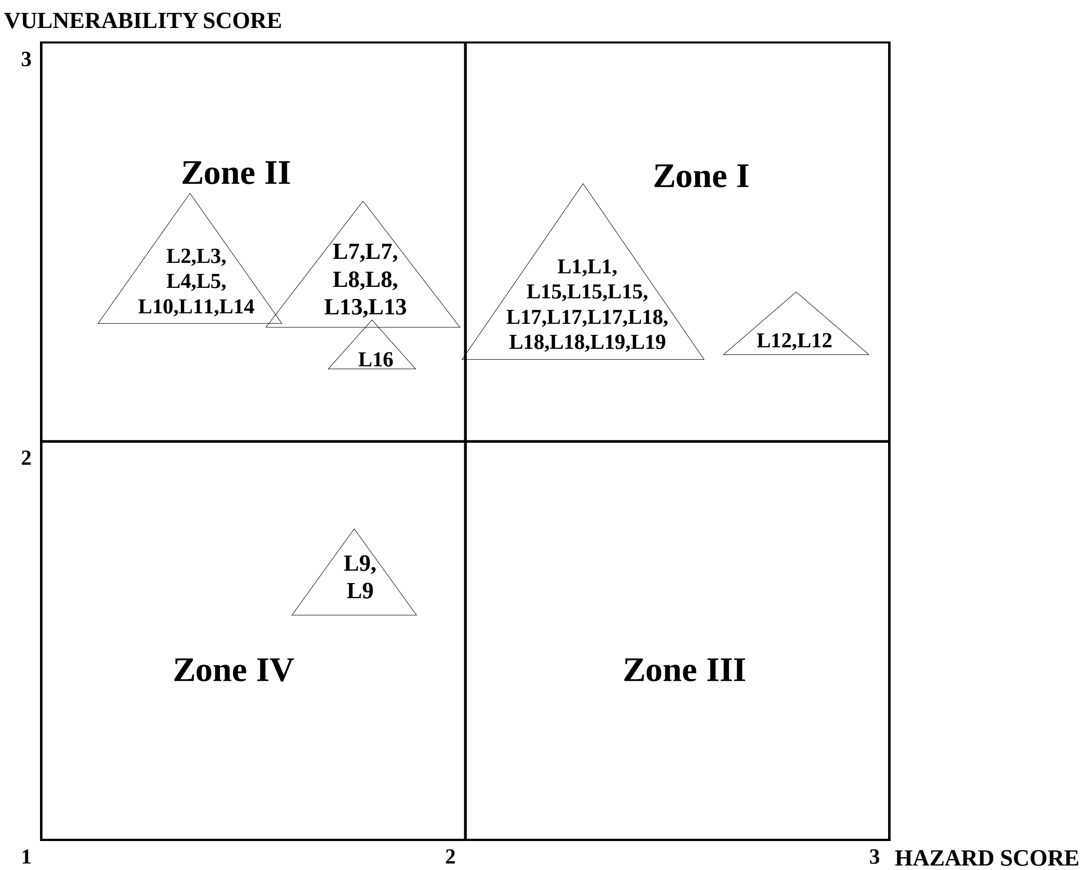


Figure 3.7: Disruption risk profile of transportation links

Out of the 31 risk events of the 20 transportation links, the risk mapping in Figure 3.7 shows that:

- 15 risk events from 6 transportation links (L1, L12, L15, L17, L18, and L19) are located in the critical disruption zone (Zone I). All the 15 risk events do not have risk management practice available. Those transportation links are from the suppliers in China and India. The company should focus on managing the disruption risk of these transportation links.

- 14 risk events from 11 transportation links (L2, L3, L4, L5, L7, L8, L10, L11, L13, L14, and L16) are located in Zone II, which indicates that the vulnerability of these transportation links could lead to possible disruptions. Six of the risk events from 3 transportation links (L7, L8, and L13) have risk management practice under preparation. The others do not have any risk management practice available.
- Two risk events from the transportation link L9 are located in the low disruption zone (Zone IV). Both events have risk management practice available. For this transportation link, the company should ensure that the existing risk management practices are effective.

In addition to the risk events identified by the company, we have also pointed out a possible disruption that may occur at crucial hubs or chokepoints (e.g., the Suez Canal, the Strait of Malacca, and the Gulf of Aden) from the Asia Pacific region to the United States. Since 19 out of 20 transportation links are operated by ship, the company is also highly vulnerable to a maritime transportation disruptions.

Managerial Implications

The company can use the disruption risk matrix to visualize the relative risk of all identified hazards. The disruption risk matrixes in Figures 3.6 and 3.7 also indicate that the company is highly vulnerable to supplier disruptions as majority of the facilities and transportation links are in the critical and high disruption risk zones, and many identified hazards do not have risk monitoring or risk mitigation strategies in place. Furthermore, the supplier S1, S17, S18, and S19 should be of primary concern because both of their facilities and transportation links are in the critical disruption risk zone. The hazards (risk events), vulnerability, and a lack of risk management practice of these suppliers could result in disruptions. We have summarized the practical risk management practices suggested in Handfield and McCormack (2008), Norrman and Jansson (2004), and Ravindran and Warsing (2013) to the company for managing suppliers' disruption risks, as shown in Table 3.22. The company should also review the disruption risk matrixes periodically as several attributes, such as country risk, logistics performance index, and availability of risk management practice, may change from time to time. New risk events could be also added into the disruption risk matrixes due to the dynamics of the supply chain environment.

Table 3.22: Practical risk management practices to manage suppliers' disruption risks

Risk Events	Recommended risk management practice
Equipment Breakdown	• A company prepares contingency plans such as back up supplier, strategic stock • Keeping scheduled meetings with suppliers for risk issues • Conduct a detailed disruption incident report • Encourage supplier to create a predictive maintenance system for detecting event or early warning system • Require suppliers to produce a detailed plan of disruption awareness and to identify supply chain risk management capabilities • Improve an aligned interests with suppliers to facilitate close communication, cooperation, and collaboration
FDA alert	• Keeping scheduled meetings with suppliers for risk issues • Improve an aligned interests with suppliers to facilitate close communication, cooperation, and collaboration • Real-time monitoring a global situation
Production constraint (Scheduling/capacity/min order qty)	• Improve an aligned interests with suppliers to facilitate close communication, cooperation, and collaboration • Increase flexibility of replenishment, supply contract
Unstable workforce	• Improve an aligned interests with suppliers to facilitate close communication, cooperation, and collaboration • Preparing contingency plans e.g. consider to have alternate or back-up suppliers • Increase product availability such as inventory or multiple inventory location to respond during the unstable workforce periods • Increase replenishment flexibility through a flexible supply contract to allow shifting order quantity across time
Short product life cycle	• Encourage suppliers to develop an advanced notice or visibility of the product life cycle state
Lack of MFG control	• Improve an aligned interests with suppliers to facilitate close communication, cooperation, and collaboration • Implement monitoring system
Flood	• Keeping scheduled meetings with suppliers for risk issues and to update situation • Improving collaboration • Encourage suppliers to develop a contingency plans • Preparing contingency plans e.g. consider to have alternate or back-up suppliers • Understand a supply flexibility of suppliers to allow shifting supply base during disruption • Increase transportation flexibility such as alternate transportation mode/route • Increase product availability such as increase safety stock, increase multiple inventory locations during the risk event period • Increase replenishment flexibility through a flexible supply contract to allow shifting order quantity across time • Consider Make-and-Buy strategy for key items to increase supply flexibility.

3.8 Conclusion

In this chapter, we presented a framework for assessing disruption risks associated with man-made and natural disasters for a global supply chain. The assessment is based on the concept that supply chain disruptions are influenced by *risk events, vulnerability* of facilities and transportation links, and *risk management practice* to cope with the risk events. We provide two numerical examples to illustrate the implementation of this framework in assessing disruption risks for facilities and transportation links. The quantified disruption risk score can be applied to develop a corporate disruption risk profile. A case study of supplier disruption risk assessment illustrates the implementation of this framework in assessing and managing disruption risks for facilities and transportation links. The assessment framework can serve as a useful guideline for practitioners to quantify disruption risk in their supply chains and to facilitate the development of risk mitigation strategies. The quantified disruption risk score can be applied to develop a corporate disruption risk profile. The risk scores of facility and transportation links can also be used in supply chain optimization models for supplier selection, facility location, and supply chain network design. Disruption risk can be set as a criterion to be minimized in these models. An application of the quantified disruption risk in a global supply chain network design problem is discussed in Chapter 4.

APPENDIX 3A: Disruption Risk Assessment Questionnaire

Disruption Risk Factors

Facility Disruption Risk

Term	Description
Hazard	A possible risk event that may cause disruption at a supplier. The risk events could be natural disaster, bankrupcy of supplier's suppliers, accident, terrorist attack, etc.
Predictability	Does location and time of the risk event predictable?
Occurrence	How often does the risk event happen?
Impact	Effects of a risk event to disrupt an operation of a facility (financial or time)
Vulnerability	Condition of the supplier's location and a country where the supplier is located
Location	A physical location of the supplier's facility compare to a location of the risk event
Political	A political condition of a country where the facility is located
Economic	An economic condition of a country where the facility is located
Financial	A financial condition of a country where the facility is located
Risk Management Practice	Availability of activities or strategies of the supplier to manage the risk event
Monitoring	Does a supplier have activities or strategies to monitor the risk event e.g. Business Continuity Standard, warning system, Key Risk Index, etc.
Mitigation	Does a supplier have activities or strategies to prevent or respond to the risk event

Transportation Disruption Risk

Hazard	A possible risk event that may cause disruption to a transportation. The risk events could be natural disaster, piracy, accident, terrorist attack, etc.
Predictability	Does location and time of the risk event predictable?
Occurrence	How often does the risk event happen?
Impact	Effects of a risk event to disrupt an operation of a transportation (financial or time)
Vulnerability	Characteristics of the transportation that relevant to the disruption
Route	A shipping path which include port of origin and port of destination and duration (in days)
Mode	Transportation mode that used to transport items between facilities
LPI	Logistics Performance Index of a country (refer to Worldbank)
Transshipment	Number of transshipment during the transportation e.g. inspection, ports of call, etc.
Risk Management	Availability of activities or strategies of the supplier to manage the risk event
Monitoring	Does a supllier or a transportation provider have activities or strategies to monitor the risk event e.g. Business Continuity Standard, warning system, Key Risk Index, etc.
Mitigation	Does a supplier or a transportation provider have activities or strategies to prevent or respond to the risk event

Disruption Risk Assessment Guideline

Predictability	**Risk Level**	**Risk Score**
Both location and time are known	Low	1
Location and time of the risk event are somewhat predictable	Moderate	2
Both location and time are unpredictable	High	3

Occurrence	**Risk Level**	**Risk Score**
The risk event rarely occurs (e.g. once in 5 years)	Low	1
The risk event occurs every other year	Moderate	2
The risk event occurs every year	High	3

Impact	**Risk Level**	**Risk Score**
Cost of impact is low/ the risk event may take a week or longer to disrupt the supplier	Low	1
Cost of impact is moderate/ the risk event may take a few days to disrupt the supplier	Moderate	2
Cost of impact is high/ the risk event could disrupt the supplier immediately	High	3

Location	**Risk Level**	**Risk Score**
The supplier seldom have an impact from the risk event	Low	1
The supplier sometimes have an impact from the risk event	Moderate	2
The supplier always have a direct impact from the risk event	High	3

Political (refer to the Political Risk Map)	**Risk Level**	**Risk Score**
Political stability of a country is high	Low	1
Political stability of a country is moderate	Moderate	2
Political stability of a country is low	High	3

Economic (refer to the Econimic Freedom)	**Risk Level**	**Risk Score**
Economic ranking of a country is high	Low	1
Economic ranking of a country is moderate	Moderate	2
Economic ranking of a country is low	High	3

Financial (refer to the Euromoney Country Risk)	**Risk Level**	**Risk Score**
Financial ranking of a country is high	Low	1
Financial ranking of a country is moderate	Moderate	2
Financial ranking of a country is low	High	3

Disruption Risk Assessment Guideline

Transportation Mode	**Risk Level**	**Risk Score**
Truck only	Low	1
Air	Moderate	2
Ship	High	3

Route	**Risk Level**	**Risk Score**
Domestic / Short duration	Low	1
Shipping path is within a region/ moderate duration	Moderate	2
Shipping path is across continent/ long duration	High	3

LPI (refer to LPI from Worldbank)	**Risk Level**	**Risk Score**
LPI of a country is high	Low	1
LPI of a country is moderate	Moderate	2
LPI of a country is low	High	3

Transshipment	**Risk Level**	**Risk Score**
Number of transshipment or ports of call is low	Low	1
Number of transshipment or ports of call is moderate	Moderate	2
Number of transshipment or ports of call is high	High	3

Control	**Risk Level**	**Risk Score**
Risk monitoring is available	Low	1
Risk monitoring is under preparation	Moderate	2
Risk monitoring is not available	High	3

Mitigation	**Risk Level**	**Risk Score**
Mitigation strategy is available	Low	1
Mitigation strategy is under preparation	Moderate	2
Mitigation strategy is not available	High	3

Chapter 4

Multi-objective Strategic Model for Global Supply Chain Network Design incorporating Disruption Risk

In this chapter, we formulate a multi-criteria optimization model to support a global supply chain network design under disruption. The decision criteria consist of profit, customer responsiveness (demand fulfillment and delivery), and disruption risk of supply chain components (facilities and transportation links). The disruption risk scores developed in Chapter 3 are used as disruption risk parameters. We apply Goal Programming (GP) techniques to handle the multiple conflicting objectives. Using the model, companies can evaluate tradeoff between benefits and risks among various design solutions. The supply chain network strategic model is the second module in the disruption risk management framework, as shown in Figure 4.1.

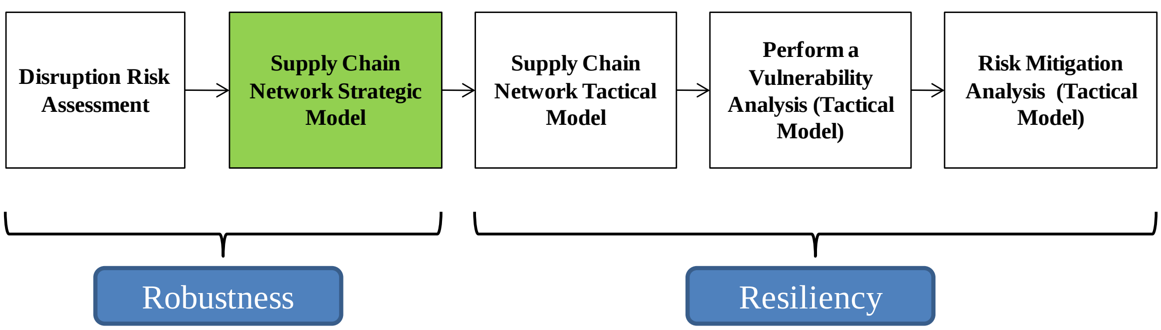


Figure 4.1: Supply Chain Network Strategic Model in a Disruption Risk Management Framework for a Global Supply Chain Network

The remainder of this chapter is organized as follows. Section 4.1 presents supply chain network design criteria and model assumptions. Section 4.2 provides a multi-criteria optimization model formulation. Section 4.3 discusses solution techniques. Section 4.4 presents a numerical example of the supply chain network design problem. Section 4.5 contains an analysis of results and discussions. Section 4.6 provides a comparison of multiple design solution using the value path method. Section 4.7 discusses an alternative approach to solve the multi-criteria mathematical problem. Finally, we present conclusion of the supply chain network design decision-making under disruption risk.

4.1 Supply Chain Network Design Criteria and Model Assumptions

A physical representation of a supply chain network consists of facilities (e.g., suppliers, manufacturing plants, distribution centers, demand zones), and transportation links. In the global supply chain network, facilities are located in different countries and multiple transportation links transport items between facilities. A typical global supply chain network is shown in Figure 4.2.

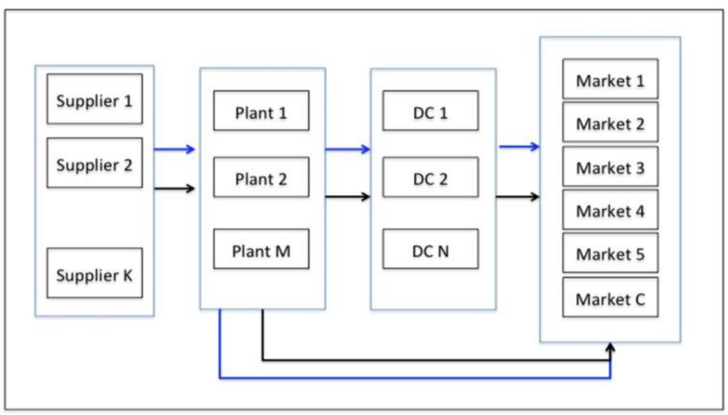


Figure 4.2: A Global Supply Chain Network

4.1.1 Supply Chain Network Design Criteria

This research considers a traditional supply chain network that consists of candidate suppliers, possible plant and distribution center locations, and customer zones. Items can be transported between facilities using multiple transportation links. Disruptions may occur to either facilities or transportation links. A company wants to design a global supply chain network that achieves five objectives: maximize profit (Z1), maximize demand fulfillment or minimize unfulfilled demand (Z2), minimize delivery time to customer (Z3), minimize facility disruption risk (Z4), and minimize disruption risk to transportation links (Z5). The supply chain network criteria are shown in Figure 4.3.

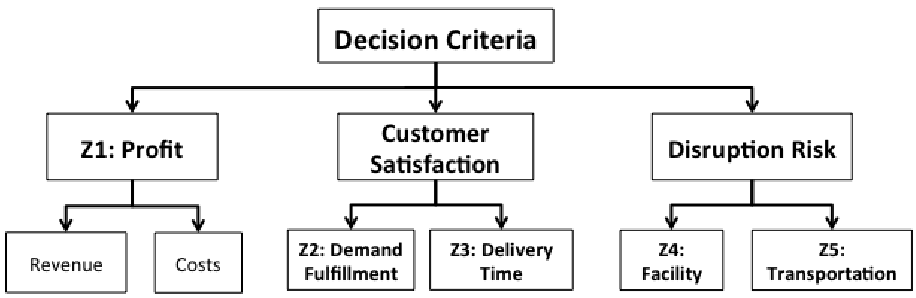


Figure 4.3: Supply Chain Network Design Criteria

The last two objectives are used to enhance the robustness of the designed global supply chain network. A supply chain component that has a lower disruption risk score is more robust to a disruption. Therefore, a supply chain network that consists of low-disruption risk supply chain components should be more robust than a supply chain network that consists of high-disruption risk components.

We formulate a multi-criteria optimization model for a multinational company in order to make the following decisions: (i) supply chain network structure, including which suppliers, manufacturing plants, and DCs to use; (ii) production and distribution planning, including which plants should produce which finished products, and which plants or DCs should distribute finished products to which customers; and (iii) transportation selection, including which transportation links should be used to ship items between facilities.

4.1.2 Model Assumptions

The strategic supply chain network design is based on the following assumptions:

- A multinational company wants to design a supply chain network for new products. A set of potential suppliers, plant locations, DCs, and transportation links are available; hence, the decisions focus on network structure and distribution planning.
- When Items (raw materials or finished products) are shipped internationally, additional costs are incurred (e.g., tariffs and import fees, export tax, etc.) that must be determined. In this study, import fees apply to raw materials that arrive at the plants because suppliers and plants are located in different countries. It is expressed as a percentage of total raw material cost. Tariffs do not apply when finished products are shipped from plants to the company-owned DCs; however export fees apply to finished products that are shipped directly from plants to customers in different countries. Export fees are calculated as a percentage of the total revenue at the plants.
- Products can be shipped directly from the plants to the demand zones if demand meets minimum level
- Business environments are deterministic. In addition, all relevant prices and costs are given in a standard currency (USD).
- Disruption risk score for facilities (suppliers, plants, and DCs) and transportation links are pre-determined by the company and may vary based on facility location. The scores are determined using the disruption risk assessment framework developed in Chapter 3.

4.2 Mathematical formulation

4.2.1 Notation

Notations used in mathematical model:

I Set of raw materials

J Set of finished products

K Set of raw materials suppliers

M Set of manufacturing plants

N Set of distribution centers

C Set of customers

f Origin nodes or facilities($f = K \cup M \cup N$)

d Destination nodes or facilities($d = M \cup N \cup C$)

U_{fd} Transportation links connecting facilities f and d

p Item representing raw material or finished product ($p \in I \cup J$)

Parameters:

D_{jc} Forecasted demand of product j to customer c (units)

f_{jc} Fraction of demand of product j to customer c that a company desires to satisfy

b_{ij} Quantity of raw material i needed to produce one unit of product j (units)

RMD_i Quantity of raw material i required based on the forecasted demand (units)

(Note: $RMD_i = \sum_j b_{ij} \sum_c D_{jc}$)

FSC_f Fixed cost of selecting facility f (FSC_k, FSC_m, FSC_n)

FSC_{pf} Fixed operating cost when assigning item p to facility f ($FSC_{ik}, FSC_{jm}, FSC_{jn}$)

FSC_{pfd} Fixed cost, which may occur, when assigning item p between facilities f and d $(FSC_{ikm}, FSC_{jmn}, FSC_{jmc}, FSC_{jnc})$

S_j Space required at a distribution center to store one unit of product j

SP_{jfc} Selling price of product j from facilities f to customer c (SP_{jmc}, SP_{jnc})

MC_{ik} Cost per unit of raw material i shipped from supplier k

PC_{jm} Unit production cost of producing product j at plant m

SC_{jn} Storage cost per space unit of product j at DC n

FTC_{ufd} Fixed transportation cost of link u if used between facilities f and d $(FTC_{ukm}, FTC_{umn}, FTC_{umc}, FTC_{unc})$

TC_{pufd} Unit shipping cost of item p via link u from facility f to facility d $(TC_{iukm}, TC_{jumn}, TC_{jumc}, TC_{junc})$

LT_{ufd} Average lead-time when using link u between facilities f and d

CAP_f Capacity of facility f (CAP_m, CAP_n)

CAP_{pf} Capacity of item p at facility f (CAP_{ik}, CAP_{jm})

MIN_{ik} Minimum order quantity to purchase raw material i from supplier k

MIN_{jm} Minimum production quantity to produce product j at plant m

$MIND$ Minimum order to allow direct shipment between a plant and a customer (cumulative over all products)

CAP_{ufd} Capacity of transportation link u between facilities f and d $(CAP_{ukm}, CAP_{umn}, CAP_{umc}, CAP_{unc})$

MIN_{ufd} Minimum quantity required in order to use transportation link u between facilities f and d $(MinCAP_{ukm}, MinCAP_{umn}, MinCAP_{umc}, MinCAP_{unc})$

VaR_f Disruption risk scores of facility f (VaR_k, VaR_m, VaR_n)

VaR_{ufd} Disruption risk score of transportation link u between facilities f and d ($VaR_{ukm}, VaR_{umn}, VaR_{umc}, VaR_{unc}$)

$\emptyset_m$ Percentage of import fees applied to the variable purchasing cost at plant m

∂_m Percentage of export fees applied to the revenue of plant m

4.2.2 Model Variables

X_f Binary variable equals to 1 if facility f is selected; 0 otherwise (X_k, X_m, X_n)

X_{pf} Binary variable equals to 1 if item p (raw material i or product j) is assigned to facility f; 0 otherwise (X_{ik}, X_{jm}, X_{jn})

X_{pfd} Binary variable equals to 1 if item p is transferred between facilities f and d; 0 otherwise ($X_{ikm}, X_{jmn}, X_{jmc}, X_{jnc}$)

X_{ufd} Binary variable equals to 1 if link u is used to ship items between facilities f and d; 0 otherwise ($X_{ukm}, X_{umn}, X_{umc}, X_{unc}$)

Q_{pufd} Quantity of item p shipped via transportation link u between facilities f and d

Y_{jm} Quantity of product j produced at plant m

W_{jc} Quantity of unfulfilled demand of product j to customer c

σ_f Fraction of items handled by facility f

δ_{ufd} Fraction of items handled by link u connecting facilities f and d

4.2.3 Objective Functions

The supply chain strategic decisions will be based on multiple objectives that include maximize profit (Z1), minimize unfulfilled demand (Z2), minimize delivery time to customers (Z3), minimize facility disruption risk (Z4), and minimize transportation link disruption risk (Z5).

- **Maximize profit of the supply chain (Z_1)**

Before tax profit of a supply chain can be determined using Equation (4.1):

$$Max\ Z1 = \left[\sum_{c\in C}\sum_{j\in J}\sum_{u\in U_{mc}}\sum_{m\in M} SP_{jmc}Q_{jumc} + \sum_{c\in C}\sum_{j\in J}\sum_{u\in U_{nc}}\sum_{n\in N} SP_{jnc}Q_{junc}\right]$$

$$-\left[\sum_{k\in K} FSC_k X_k + \sum_{m\in M} FSC_m X_m + \sum_{n\in N} FSC_n X_n\right]$$

$$-\left[\sum_{k\in K}\sum_{i\in I} FSC_{ik}X_{ik} + \sum_{k\in K}\sum_{i\in I} MC_{ik}\left(\sum_{m\in M}\sum_{u\in U_{km}} Q_{iukm}\right)\right] -$$

$$\left[\left(\sum_{m\in M}\sum_{j\in J} FSC_{jm}X_{jm}\right) + \left(\sum_{m\in M}\sum_{j\in J} PC_{jm}Y_{jm}\right)\right]$$

$$-\left[\left(\sum_{n\in N}\sum_{j\in J} FSC_{jn}X_{jn}\right) + \left(\sum_{n\in N}\sum_{j\in J} SC_{jn}S_j\left(\sum_{m\in M}\sum_{u\in U_{mn}} Q_{jumn}\right)\right)\right]$$

$$-\left[\left(\sum_{d\in D}\sum_{f\in F}\sum_{u\in U_{fd}} FTC_{ufd}X_{ufd}\right) + \left(\sum_{d\in D}\sum_{f\in F}\sum_{u\in U_{fd}}\sum_{p\in P} TC_{pufd}Q_{pufd}\right)\right]$$

$$-\left[\sum_{d\in D}\sum_{f\in F}\sum_{p\in I\cup J} FSC_{pfd}X_{pfd}\right]$$

$$-\left[\sum_{m\in M}\emptyset_m\sum_{k\in K}\sum_{i\in I} MC_{ik}\left(\sum_{u\in U_{km}} Q_{iukm}\right) + \sum_{m\in M}\partial_m\sum_{c\in C}\sum_{j\in J} SP_{jc}\left(\sum_{u\in U_{mc}} Q_{jumc}\right)\right] \quad (4.1)$$

Profit is the difference between revenue and total cost. The first component represents the revenues from plants and DCs. Next are the facility location cost; raw material purchasing cost, which consists of fixed purchasing cost and variable cost; production cost, which consists of fixed cost of producing a specific product at a specific plant and variable production cost; distribution center cost, which consists of the fixed operating cost and variable cost calculated based on the space used; transportation cost, which consists of fixed transportation cost and variable cost based on shipping quantities; additional fixed administration cost that may occur when assigning an item between facilities; and the cross-sourcing cost incurred at plants when raw materials are imported from suppliers and finished products are exported to customers.

- **Minimize Unfulfilled Demand (or Maximize Demand Fulfillment) (Z_2)**

Since the first objective is to maximize profit, it is possible that some customer demands may not be fully met. This objective is introduced to achieve customer responsiveness by maximizing customer demand fulfillment, in other words, minimizing the unfulfilled demand or shortages, as shown in Equation (4.2).

$$Min\ Z_2 = \sum_{c \in C} \sum_{j \in J} W_{jc} \tag{4.2}$$

- **Minimize Delivery Time to Customer (Z_3)**

Beside the demand fulfillment, the delivery time to customer is another customer responsiveness measure. Given the estimated lead-times between plants and customers and between DCs to customers based on the transportation links used, we multiply these values with the amount of customer demand that is fulfilled by plants and DCs. Even though this value does not represent the true delivery time to customers, it provides a useful measure of responsiveness in terms of volume-weighted lead-time. If a link with a long travel time carries a huge amount of demand, then the volume weighted delivery time value will be high. Hence, the customer demand should be allocated to each link in such a way that the total volume weighted delivery time is minimal. From equation (4.3), the first component represents the delivery time from plants to customers, while the second one represents the delivery time from DCs to customers.

$$Min\ Z_3 = \sum_{c \in C} \sum_{m \in M} \sum_{u \in U_{mc}} LT_{umc} \times \left(\sum_{j} Q_{jumc} \right) + \sum_{c \in C} \sum_{n \in N} \sum_{u \in U_{nc}} LT_{unc} \times \left(\sum_{j} Q_{junc} \right) \quad (4.3)$$

- **Disruption Risks**

Supply chain disruption could come from either a disruption to a facility or a disruption of the transportation network. In addition, it depends upon the quantity (flow) handled by a particular node (link). If a node (link) with high disruption risks value accounts for a large amount of flow, the disruption risk to the supply chain will be high. Hence, items should be allocated to each node and link in such a way that the "flow weighted" disruption risk value of the whole supply chain is minimal. In this study, we consider two types of disruption risk: facility disruption risk and transportation disruption risk.

- **Minimize Disruption Risk of Facility (Z_4)**

Facility disruption risk is the summation of disruption risk of all individual facility in the supply chain network, which includes suppliers, manufacturing plants, and DCs, as shown in Equation (4.4).

$$Min\ Z_4 = \left(\sum_{f \in F} \sigma_f VaR_f \right) \quad (4.4)$$

where

σ_f are unknown values representing the fraction of items handled by each location f. For example, σ_k is the fraction of raw materials supplied by supplier k, σ_m is the fraction of finished products produced by each plant, and σ_n is the fraction of finished products handled by each DC.

$$\sigma_k = \frac{\sum_{m \in M} \sum_{u \in U_{km}} \sum_{i \in I} Q_{iukm}}{\sum_{i \in I} \sum_{j \in J} b_{ij} \left(\sum_{c \in C} D_{jc} \right)} \tag{4.4.1}$$

$$\sigma_m = \frac{\sum_{j \in J} Y_{jm}}{\sum_{c \in C} \sum_{j \in J} D_{jc}} \tag{4.4.2}$$

$$\sigma_n = \frac{\sum_{c \in C} \sum_{u \in U_{nc}} \sum_{j \in J} Q_{junc}}{\sum_{c \in C} \sum_{j \in J} D_{jc}} \tag{4.4.3}$$

- **Minimize Disruption Risk of Transportation (Z_5)**

Transportation disruption risk is the summation of disruption risks of all transportation links between facilities in the supply chain network.

$$Min\, Z_5 = \left(\sum_{d \in D} \sum_{f \in F} \sum_{u \in U_{fd}} \delta_{ufd} VaR_{ufd} \right) \tag{4.5}$$

Where δ_{ufd} are unknown values representing the fraction of items carried by each transportation link u between origin node (f) and destination node (d). For example, supplier-plant (δ_{ukm}), plant-DC (δ_{umn}), plant-customer (δ_{umc}) and DC-customer (δ_{unc}) are defined as follows.

$$\delta_{ukm} = \frac{\sum_{i \in I} Q_{iukm}}{\sum_{i \in I} \sum_{j \in J} b_{ij} \left(\sum_{c \in C} D_{jc} \right)} \tag{4.5.1}$$

$$\delta_{umn} = \frac{\sum_{j \in J} Q_{jumn}}{\sum_{c \in C} \sum_{j \in J} D_{jc}} \tag{4.5.2}$$

$$\delta_{umc} = \frac{\sum_{j \in J} Q_{jumc}}{\sum_{c \in C} \sum_{j \in J} D_{jc}} \tag{4.5.3}$$

$$\delta_{unc} = \frac{\sum_{j \in J} Q_{junc}}{\sum_{c \in C} \sum_{j \in J} D_{jc}} \tag{4.5.4}$$

4.2.4 Model Constraints

4.2.4.1 Demand fulfillment constraints:

Since the supply chain network aims to achieve maximum profit, it is possible that all customer demands may not be fulfilled. Constraint (4.6) ensures that customer demands are satisfied to the extent desired by the company. Constraint (4.7) allows the company to specify different level of customer responsiveness, especially when shortages occur due to disruptions.

$$\left(\sum_{m\in M}\sum_{u\in U_{mc}} Q_{jumc} + \sum_{n\in N}\sum_{u\in U_{nc}} Q_{junc}\right) + W_{jc} = D_{jc} \qquad \forall j \in J, \forall c \in C \qquad (4.6)$$

$$W_{jc} \leq (1 - f_{jc})D_{jc} \qquad \forall j \in J, \forall c \in C \qquad (4.7)$$

Note that the right hand side of Equation 4.7 represents the maximum shortage allowed.

4.2.4.2 Supplier selection and capacity constraints:

Raw material i can be purchased from supplier k if supplier k is selected:

$$X_{ik} \leq X_k \qquad \forall i \in I, \forall k \in K \qquad (4.8)$$

Plant m can purchase raw material i from supplier k if supplier k is selected to supply the material:

$$X_{ikm} \leq X_{ik} \qquad \forall i \in I, \forall k \in K, \forall m \in M \qquad (4.9)$$

Constraint 4.10 is to ensure that quantity of raw material i is sufficient to meet forecasted demand:

$$\sum_{m\in M}\sum_{k\in K}\sum_{u\in U_{km}} Q_{iukm} \geq RMD_i \qquad \forall i \in I \qquad (4.10)$$

where $RMD_i = \sum_{j\in J} b_{ij} \sum_{c\in C} D_{jc}$

Constrain 4.11 ensures that the total amount of raw material purchased and shipped from a supplier to the plants cannot exceed the capacity of the selected supplier and must meet minimum order quantity:

$$MIN_{ik}X_{ik} \leq \sum_{m \in M} \sum_{u \in U_{km}} Q_{iukm} \leq CAP_{ik}X_{ik} \qquad \forall i \in I, \forall k \in K \quad (4.11)$$

4.2.4.3 Plant selection and production capacity

Finished product j can be produced at plant m if plant m is selected:

$$X_{jm} \leq X_m \qquad \forall j \in J, \forall m \in M \quad (4.12)$$

DC n can receive a finished product j from plant m if plant m produces product j and DC n is opened for product j:

$$X_{jmn} \leq X_{jm} \qquad \forall j \in J, \forall m \in M, \forall n \in N \quad (4.13)$$

$$X_{jmn} \leq X_{jn} \qquad \forall j \in J, \forall m \in M, \forall n \in N \quad (4.14)$$

Plant m can ship product j directly to customer c if product j is produced at plant m:

$$X_{jmc} \leq X_{jm} \qquad \forall j \in J, \forall m \in M, \forall c \in C \quad (4.15)$$

Constraint 4.16 ensures that quantity of product j produced at plant m meets the minimum production requirement and does not exceed its capacity:

$$MIN_{jm}X_{jm} \leq Y_{jm} \leq CAP_{jm}X_{jm} \qquad \forall j \in J, \forall m \in M \quad (4.16)$$

Constraint 4.17 ensures that the production quantities are limited by quantity of each raw material received from suppliers:

$$\sum_{j \in J} b_{ij}Y_{jm} \leq \sum_{k \in K} \sum_{u \in U_{km}} Q_{iukm} \qquad \forall i \in I, \forall m \in M \quad (4.17)$$

Constraint 4.18 ensures that the total amount of raw material i used cannot exceed the amount of the material purchased from suppliers:

$$\sum_{j \in J} b_{ij} \sum_{m \in M} Y_{jm} \leq \sum_{m \in M} \sum_{k \in K} \sum_{u \in U_{km}} Q_{iukm} \qquad \forall i \in I \quad (4.18)$$

Constraints 4.19 and 4.20 ensure that the production quantities meet the minimum demand fulfillment target but not to produce more than the forecasted demand:

$$\sum_{m \in M} Y_{jm} \geq \sum_{c \in C} f_{jc}D_{jc} \qquad \forall j \in J \quad (4.19)$$

$$\sum_{m \in M} Y_{jm} \leq \sum_{c \in C} D_{jc} \qquad \forall j \in J \quad (4.20)$$

Constraint 4.21 ensures that the total quantity of product j shipped from plant m to the customers and DCs cannot exceed the amount that is produced at the plant:

$$\sum_{u \in U_{mn}} \sum_{n \in N} Q_{jumn} + \sum_{u \in U_{mc}} \sum_{c \in C} Q_{jumc} \leq Y_{jm} \qquad \forall j \in J, \forall m \in M \quad (4.21)$$

4.2.4.4 DC selection and storage capacity

A finished product j can be stored at the distribution center if the DC is selected:

$$X_{jn} \leq X_n \qquad \forall j \in J, \forall n \in N \quad (4.22)$$

DC n can respond to a demand of a finished product j at a customer c if the product is stored at the DC:

$$X_{jnc} \leq X_{jn} \qquad \forall j \in J, \forall c \in C, \forall n \in N \quad (4.23)$$

Total space used by all products cannot exceed the capacity of the DC:

$$\sum_{j \in J} S_j \left(\sum_{m \in M} \sum_{u \in U_{mn}} Q_{jumn} \right) \leq CAP_n X_n \qquad \forall n \in N \quad (4.24)$$

Quantity of product j shipped out of DC n to customers cannot exceed the available quantity that is received from the plants:

$$\sum_{u \in U_{nc}} \sum_{c \in C} Q_{junc} \leq \sum_{u \in U_{mn}} \sum_{m \in M} Q_{jumn} \qquad \forall j \in J, \forall n \in N \quad (4.25)$$

4.2.4.5 Transportation link operation:

Transportation link u, between node f and destination d, can be used if items are assigned between the facilities:

$$X_{ufd} \leq \sum_{p \in I \cup J} X_{pfd} \qquad \forall u \in U_{fd}, \forall f \in K \cup M \cup N, \forall d \in M \cup N \cup C \quad (4.26)$$

<u>4.2.4.6 Transportation capacity</u>: Quantity shipped by each transportation link must be larger than the minimum requirement of the transportation link, but cannot exceed its capacity (4.27). In addition, a direct shipment between plant m and customer c is allowed if the minimum order quantity is met ($MinD$) (4.28):

$$MIN_{ufd}X_{ufd} \leq \sum_{p \in P} Q_{pufd} \leq CAP_{ufd}X_{ufd} \quad \forall u \in U_{fd}, \forall p \in I \cup J, \forall f \in K \cup M \cup N, \forall d \in M \cup N \cup C \quad (4.27)$$

$$Q_{jumc} \geq MIND \times X_{umc} \quad \forall j \in J, u \in U_{mc}, \forall m \in M, \forall c \quad (4.28)$$

<u>4.2.4.7 Binary and non-negativity constraints</u> (4.29)

$$X_f \in \{0,1\} \quad \forall f \in K \cup M \cup N$$

$$X_{pf} \in \{0,1\} \quad \forall p \in I \cup J, \forall f \in K \cup M \cup N$$

$$X_{pfd} \in \{0,1\} \quad \forall p \in I \cup J, \forall f \in K \cup M \cup N, \forall d \in M \cup N \cup C$$

$$X_{ufd} \in \{0,1\} \quad \forall u \in U_{fd}, \forall f \in K \cup M \cup N, \forall d \in M \cup N \cup C$$

$$Q_{pufd} \geq 0 \quad \forall u \in U_{fd}, \forall p \in I \cup J, \forall f \in K \cup M \cup N, \forall d \in M \cup N \cup C$$

$$Y_{jm} \geq 0 \quad \forall j \in J, \forall m \in M$$

$$W_{jc} \geq 0 \quad \forall j \in J, \forall c \in C$$

$$\sigma_f \geq 0 \quad \forall f \in K \cup M \cup N$$

$$\delta_{ufd} \geq 0 \quad \forall u \in U_{fd}, \forall f \in K \cup M \cup N, \forall d \in M \cup N \cup C$$

4.3 Solution technique by Goal Programming (GP)

The supply chain network design model developed in this research is a multi-criteria mathematical programming problem (MCMP). To handle the multiple and conflicting objectives, the Goal Programming approach will be applied. Goal programming uses pre-specified preferences of the decision maker to solve the MCMP problems. In this approach, target levels for achievement are obtained for all objectives. In addition, the relative importances of achieving the targets are also specified. These target values are treated as goal constraints that the decision maker desires to achieve. However, they may or may not be achievable. The goal programming approach attempts to find an optimal solution that comes as close to the targets as possible corresponding to the decision makers' priorities. The objective function in GP is to minimize the deviations from the target values. There are four types of GP formulations: (i) Preemptive Goal Programming (P-GP); (ii) Non-preemptive Goal Programming (NP-GP); (iii) MinMax Goal Programming (or Tchebysheff GP); and (iv) Fuzzy Goal Programming. These formulations differ in how the objective functions are prioritized and target deviations are treated. A detailed description of GP methods can be found in Masud and Ravindran (2008). In this research, we apply the preemptive GP and the non-preemptive GP formulations to solve the supply chain network design model.

4.3.1 Preemptive Goal Programming (P-GP)

In P-GP, the objective functions are ranked based on the ordinal preferences of the decision maker. In other words, high priority goals are achieved before lower priority goals are considered. In addition, deviations from target values associated with each objective are minimized in a sequence of priorities (Masud & Ravindran, 2008). To formulate the P-GP model, the following parameters and variables are used.

<u>Parameters:</u>

P_i Priority of goal i for the preemptive GP formulation

Z_i Objective functions denoting profit, demand fulfillment, delivery time, and disruption risk $(i = 1, 2, 3, 4, 5)$.

$IDEAL_i$ Ideal value of objective i. The ideal value of objective i can be obtained by solving a single objective optimization problem (ignoring other objectives). For example, the ideal value of profit is obtained by solving the problem to maximize profit ignoring the other objectives.

$TARG_i$ Target value of objective i. This value is set by the decision maker based on the ideal value and whether the objective is to maximize or minimize. For example, a profit target may be set at 95% of the ideal profit, while delivery time target may be set at 110% of the ideal value.

Additional Variables:

d_i^+ Positive deviation from target value of objective i

d_i^- Negative deviation from target value of objective i

P-GP Objective Function:

$$\text{Min} \quad P_1(d_1^-) + P_2(d_2^+) + P_3(d_3^+) + P_4(d_4^+) + P_5(d_5^+)$$

Subject to

$$Z_1 - d_1^+ + d_1^- = TARG_1 \quad \text{(Profit)}$$

$$Z_2 - d_2^+ + d_2^- = TARG_2 \quad \text{(Unfulfilled demand)}$$

$$Z_3 - d_3^+ + d_3^- = TARG_3 \quad \text{(Delivery time)}$$

$$Z_4 - d_4^+ + d_4^- = TARG_4 \quad \text{(Facility Disruption risk)}$$

$$Z_5 - d_5^+ + d_5^- = TARG_5 \quad \text{(Transportation Disruption risk)}$$

$$d_i^+, d_i^- \geq 0 \qquad i = 1, \ldots, 5$$

In our model, it is assumed that the decision maker ranks the priorities (from high to low) as P1: profit, P2: delivery time, P3: facility disruption risk, P4: transportation link disruption risk, and P5: unfulfilled demand. Hence, the objective function for the Goal Programming model is to minimize the deviations from the target values defined for each objective. For instance, minimize the negative deviation of the profit (d_1^-), minimize the positive deviation of the delivery lead-time (d_3^+), minimize the positive deviation of the facility disruption risk (d_4^+), minimize the positive deviation of the transportation disruption risk (d_5^+), and minimize the positive deviation of the unfulfilled demand (d_2^+). The preemptive goal programming formulation would be

$$Min \qquad P_1 d_1^- + P_2 d_3^+ + P_3 d_4^+ + P_4 d_5^+ + P_5 d_2^+ \qquad (4.30)$$

Subject to

<u>Profit goal:</u>

$$\left[\sum_{c\in C}\sum_{j\in J}\sum_{u\in U_{mc}}\sum_{m\in M} SP_{jmc}Q_{jumc} + \sum_{c\in C}\sum_{j\in J}\sum_{u\in U_{nc}}\sum_{n\in N} SP_{jnc}Q_{junc}\right] - \left[\sum_{k\in K} FSC_k X_k + \sum_{m\in M} FSC_m X_m + \sum_{n\in N} FSC_n X_n\right]$$

$$- \left[\sum_{k\in K}\sum_{i\in I} FSC_{ik}X_{ik} + \sum_{k\in K}\sum_{i\in I} MC_{ik}\left(\sum_{m\in M}\sum_{u\in U_{km}} Q_{iukm}\right)\right]$$

$$- \left[\left(\sum_{m\in M}\sum_{j\in J} FSC_{jm}X_{jm}\right) + \left(\sum_{m\in M}\sum_{j\in J} PC_{jm}Y_{jm}\right)\right]$$

$$- \left[\left(\sum_{n\in N}\sum_{j\in J} FSC_{jn}X_{jn}\right) + \left(\sum_{n\in N}\sum_{j\in J} SC_{jn}S_j\left(\sum_{m\in M}\sum_{u\in U_{mn}} Q_{jumn}\right)\right)\right]$$

$$- \left[\left(\sum_{d\in D}\sum_{f\in F}\sum_{u\in U_{fd}} FTC_{ufd}X_{ufd}\right) + \left(\sum_{d\in D}\sum_{f\in F}\sum_{u\in U_{fd}}\sum_{p\in P} TC_{pufd}Q_{pufd}\right)\right] - \left[\sum_{d\in D}\sum_{f\in F}\sum_{p\in I\cup J} FSC_{pfd}X_{pfd}\right]$$

$$- \left[\sum_{m\in M} \emptyset_m \sum_{k\in K}\sum_{i\in I} MC_{ik}\left(\sum_{u\in U_{km}} Q_{iukm}\right) + \sum_{m\in M} \partial_m \sum_{c\in C}\sum_{j\in J} SP_{jc}\left(\sum_{u\in U_{mc}} Q_{jumc}\right)\right] - d_1^+ + d_1^- = TARG_1 \quad (4.31)$$

Unfulfilled demand goal:

$$\sum_{c\in C}\sum_{j\in J} W_{jc} - d_2^+ + d_2^- \quad = \quad TARG_2 \tag{4.32}$$

Delivery time to customer goal:

$$\sum_{c\in C}\sum_{m\in M}\sum_{u\in U_{mc}} LT_{umc} \times \left(\sum_{j\in J} Q_{jumc}\right) + \sum_{c\in C}\sum_{n\in N}\sum_{u\in U_{nc}} LT_{unc} \times \left(\sum_{j\in J} Q_{junc}\right) - d_3^+ + d_3^- \quad = \quad TARG_3 \tag{4.33}$$

Facility disruption risk goal:

$$\left(\sum_{k\in K} \sigma_k VaR_k\right) + \left(\sum_{m\in M} \sigma_m VaR_m\right) + \left(\sum_{n\in N} \sigma_n VaR_n\right) - d_4^+ + d_4^- \quad = TARG_4 \tag{4.34}$$

Transportation link disruption risk goal:

$$\left(\sum_{d\in D}\sum_{f\in F}\sum_{u\in U_{fd}} \delta_{ufd} VaR_{ufd}\right) - d_5^+ + d_5^- \quad = TARG_5 \tag{4.35}$$

Non-negativity constraints:

$$d_i^+, d_i^- \quad \geq \quad 0 \qquad i = 1, \dots, 5 \tag{4.36}$$

The model minimizes equation (4.30) subject to the goal constraints given by equations (4.31) – (4.36) and real constraints given by equations (4.6) – (4.29).

4.3.2 Non-preemptive Goal Programming

In NP-GP, numerical weights are used to indicate the relative importance of the objective functions. Several methods exist for estimating criteria weights, such as simple rating method, pair-wise comparison method, Borda Count, and Analytic Hierarchy Process (AHP). Section 4.2.3 gives an overview of these method for determining criteria weights. It is important to note that the objectives must be scaled due to differences in units and the magnitude of the objectives

(Masud & Ravindran, 2008). The NP-GP formulation for the supply chain network design problem is given below:

NP-GP Objective Function

$$\text{Min} \qquad W_1(d_1^-) + W_2(d_2^+) + W_3(d_3^+) + W_4(d_4^+) + W_5(d_5^+)$$

Subject to

$$Z_1 - d_1^+ + d_1^- = TARG_1 \quad \text{(Profit)}$$

$$Z_2 - d_2^+ + d_2^- = TARG_2 \quad \text{(Unfulfilled demand)}$$

$$Z_3 - d_3^+ + d_3^- = TARG_3 \quad \text{(Delivery time)}$$

$$Z_4 - d_4^+ + d_4^- = TARG_4 \quad \text{(Disruption risk of facility)}$$

$$Z_5 - d_5^+ + d_5^- = TARG_5 \quad \text{(Disruption risk of transportation)}$$

$$W_1 + W_2 + W_3 + W_4 + W_5 = 1$$

$$d_i^+, d_i^- \geq 0 \qquad i = 1, \dots, 5$$

where

W_i Cardinal weight of goal i for a non-preemptive GP formulation

To scale each objective, the objective equation is divided by the target value such that the new right-hand-side value is 1. For example, the scaled equation for unfulfilled demand would be

$$\frac{\sum_c \sum_j W_{jc}}{TARG_2} - d_2^+ + d_2^- = 1$$

For our model, the objective function of the non-preemptive goal programming formulation would be

$$Min \qquad W_1 d_1^- + W_2 d_2^+ + W_3 d_3^+ + W_4 d_4^+ + W_5 d_5^+ \tag{4.37}$$

Subject to

Profit goal:

$$\frac{1}{TARG_1}\left\{\left[\sum_{c\in C}\sum_{j\in J}\sum_{u\in U_{mc}}\sum_{m\in M} SP_{jmc}Q_{jumc} + \sum_{c\in C}\sum_{j\in J}\sum_{u\in U_{nc}}\sum_{n\in N} SP_{jnc}Q_{junc}\right]\right.$$

$$-\left[\sum_{k\in K} FSC_k X_k + \sum_{m\in M} FSC_m X_m + \sum_{n\in N} FSC_n X_n\right]$$

$$-\left[\sum_{k\in K}\sum_{i\in I} FSC_{ik}X_{ik} + \sum_{k\in K}\sum_{i\in I} MC_{ik}\left(\sum_{m\in M}\sum_{u\in U_{km}} Q_{iukm}\right)\right]$$

$$-\left[\left(\sum_{m\in M}\sum_{j\in J} FSC_{jm}X_{jm}\right) + \left(\sum_{m\in M}\sum_{j\in J} PC_{jm}Y_{jm}\right)\right]$$

$$-\left[\left(\sum_{n\in N}\sum_{j\in J} FSC_{jn}X_{jn}\right) + \left(\sum_{n\in N}\sum_{j\in J} SC_{jn}S_j\left(\sum_{m\in M}\sum_{u\in U_{mn}} Q_{jumn}\right)\right)\right]$$

$$-\left[\left(\sum_{d\in D}\sum_{f\in F}\sum_{u\in U_{fd}} FTC_{ufd}X_{ufd}\right) + \left(\sum_{d\in D}\sum_{f\in F}\sum_{u\in U_{fd}}\sum_{p\in P} TC_{pufd}Q_{pufd}\right)\right]$$

$$-\left[\sum_{d\in D}\sum_{f\in F}\sum_{p\in I\cup J} FSC_{pfd}\,X_{pfd}\right]$$

$$\left.-\left[\sum_{m\in M}\emptyset_m\sum_{k\in K}\sum_{i\in I} MC_{ik}\left(\sum_{u\in U_{km}} Q_{iukm}\right) + \sum_{m\in M}\partial_m\sum_{c\in C}\sum_{j\in J} SP_{jc}\left(\sum_{u\in U_{mc}} Q_{jumc}\right)\right]\right\} - d_1^+ + d_1^-$$

$$= 1 \qquad (4.38)$$

Unfulfilled demand goal:

$$\frac{1}{TARG_2}\left\{\sum_{c\in C}\sum_{j\in J} W_{jc}\right\} - d_2^+ + d_2^- = 1 \qquad (4.39)$$

Delivery time to customer goal:

$$\frac{1}{TARG_3}\left\{\sum_{c\in C}\sum_{m\in M}\sum_{u\in U_{mc}} LT_{umc}\times\left(\sum_{j\in J} Q_{jumc}\right) + \sum_{c\in C}\sum_{n\in N}\sum_{u\in U_{nc}} LT_{unc}\times\left(\sum_{j} Q_{junc}\right)\right\} - d_3^+ + d_3^-$$

$$= 1 \qquad (4.40)$$

<u>Facility disruption risk goal:</u>

$$\frac{1}{TARG_4}\left\{\left(\sum_{k\in K}\sigma_k VaR_k\right) + \left(\sum_{m\in M}\sigma_m VaR_m\right) + \left(\sum_{n\in N}\sigma_n VaR_n\right)\right\} - d_4^+ + d_4^- = 1 \tag{4.41}$$

<u>Transportation link disruption risk goal:</u>

$$\frac{1}{TARG_5}\left\{\left(\sum_{d\in D}\sum_{f\in F}\sum_{u\in U_{fd}}\delta_{ufd} VaR_{ufd}\right)\right\} - d_5^+ + d_5^- = 1 \tag{4.42}$$

Non-negativity constraints:

$$d_i^+, d_i^- \geq 0 \qquad i = 1, \ldots, 5 \tag{4.43}$$

The model minimizes equation (4.37) subject to goal constraints given by equations (4.38) – (4.43) and real constraints given by equations (4.6) – (4.29).

4.3.3 Computing Criteria Weights

To obtain the numerical weights of the decision criteria, simple rating method, Borda Count, and AHP method are used in this research. For the rating method, a decision maker assigns a score for each criterion (scale of 1-10) and the scores are normalized the score to obtain numerical weights (Masud & Ravindran, 2008). It is a quick and easy way to determine a decision maker's preferences, but it does not include the preference intensity. In Borda Count, the decision maker gives a pairwise comparison of criteria, which is then used to get the weights. AHP is the process of comparing criteria in pairs to judge which criterion is preferred and the strength of preference (Portillo, 2009; Ravindran et al., 2010). However, it is important to test the consistency of the decision maker. The cardinal weights from the simple rating method and AHP method will be used in the non-preemptive goal programming model. The following section illustrates the criteria weights calculations using the simple rating method and the pairwise comparison method with strength of preference.

4.3.3.1 Rating Method

In the rating method, a decision maker assigns a score for each criterion from 1-10, where 1 is least important and 10 is most important. Table 4.1 presents a rating of the five criteria. Weights are calculated by normalizing the rating scores. Then, weight values of profit, demand fulfillment, delivery time, facility disruption risk, and transportation disruption risk are **0.45, 0.10, 0.25, 0.10, and 0.10,** respectively.

Table 4.1: Rating score and weights from a rating method for criteria

Criteria	Score (1-10)	Weight (score/total)	Weight
Z1. Profit	9	9/20	0.45
Z2. Demand Fulfillment	2	2/20	0.10
Z3. Delivery Time	5	5/20	0.25
Z4. Facility Disruption Risk	2	2/20	0.10
Z5: Transportation Disruption Risk	2	2/20	0.10
	20		

4.3.3.2 Borda Count

In Borda Count, a decision maker compares criteria in pairs to judge which criterion is more important. Table 4.2 illustrates a pairwise comparison of criteria for our model.

Table 4.2: Pairwise comparison of criteria

Criteria	Preference
Profit – Demand fulfillment	Profit
Profit – Delivery time	Profit
Profit – Facility Disruption risk	Profit
Profit – Transportation Disruption risk	Profit
Demand fulfillment – Delivery time	Delivery time
Demand fulfillment – Facility Disruption risk	Equal
Demand fulfillment – Transportation Disruption risk	Equal
Delivery time – Facility Disruption risk	Delivery time
Delivery time – Transportation Disruption risk	Delivery time
Facility Disruption risk - Transportation Disruption risk	Equal

Let k denote the number of criteria and C_{ij} indicate the preference of criterion C_i with criterion C_j. We set $C_{ij} = 1, C_{ji} = 0$ if C_i is preferred over C_j, and $C_{ij} = 0, C_{ji} = 1$ if C_j is preferred over C_i, and $C_{ij} = C_{ji} = 1$ if there is no preference. Note that $C_{ii} = 1$. Next, we calculate the criterion totals, $t_i = \sum_{j=1}^{k} C_{ij}$ and criterion weights $w_i = t_i / \sum_{i=1}^{k} t_i$ (Ravindran & Wadhwa, 2009). Table 4.3 presents the criterion totals and criterion weights using the preferences given in Table 4.2.

Table 4.3: Weights by Borda Count

	Profit	Demand fulfillment	Delivery time	Facility Disruption Risk	Transportation Disruption Risk	Criterion total	Criterion Weights	
Profit	1	1	1	1	1	5	5/18	0.2778
Demand fulfillment	0	1	0	1	1	3	3/18	0.1667
Delivery time	0	1	1	1	1	4	4/18	0.2222
Facility Disruption risk	0	1	0	1	1	3	3/18	0.1667
Transportation Disruption risk	0	1	0	1	1	3	3/18	0.1666
						18		1.0000

4.3.3.3 AHP

AHP uses the pairwise comparison and the strength of preference. Here, the decision maker will also identify the level of the preference between each pair of criteria using the preference scale in Table 4.4.

Table 4.4: Preference strength in AHP

Preference	Score
Equally Important	1
Slightly more important	3
Stongly more important	5
Very strongly more important	7
Absolutely more important	9

Suppose a decision maker provides the preference comparison and the strength of preference, as shown in Table 4.5.

Table 4.5: Preference strength of criteria

Criteria	Preference	Strength of preference
Profit – Demand fulfillment	Profit	8
Profit – Delivery time	Profit	6
Profit – Facility Disruption risk	Profit	8
Profit – Transportation Disruption risk	Profit	8
Demand fulfillment – Delivery time	Delivery time	6
Demand fulfillment – Facility Disruption risk	Equal	1
Demand fulfillment – Transportation Disruption risk	Equal	1
Delivery time – Facility Disruption risk	Delivery time	6
Delivery time – Transportation Disruption risk	Delivery time	6
Facility Disruption risk - Transportation Disruption risk	Equal	1

From Table 4.5, the preference matrix is established and each criterion score is normalized in order to calculate criterion totals and criterion weights as shown in Table 4.6.

Table 4.6: Strength of preference matrix from a decision maker

Weight by strength of preference	**Profit**	**Demand fulfillment**	**Delivery time**	**Facility Disruption Risk**	**Transportation Disruption risk**		
Profit	1	8	6	8	8		
Demand fulfillment	1/8	1	1/6	1	1		
Delivery time	1/6	6	1	6	6		
Facility Disruption risk	1/8	1	1/6	1	1		
Transportation Disruption risk	1/8	1	1/6	1	1		
Sum	1.5416	17	7.5	17	17		
Normalization	**Profit**	**Demand fulfillment**	**Delivery time**	**Facility Disruption Risk**	**Transportation Disruption risk**	**Sum**	**Weight**
Profit	0.6486	0.47060	0.8	0.47060	0.4706	2.8604	0.572
Demand fulfillment	0.0811	0.0588	0.0222	0.0588	0.0588	0.2797	0.056
Delivery time	0.1081	0.3529	0.1333	0.3529	0.3529	1.3001	0.260
Facility Disruption risk	0.0811	0.0588	0.0222	0.0588	0.0588	0.2797	0.056
Transportation Disruption risk	0.0811	0.0588	0.0222	0.0588	0.0588	0.2797	0.056
						4.9996	1.000

Once the criteria weights have been determined, AHP checks whether the preference matrix is consistent. The consistency check can be done using Eigen values and Eigen vectors. If the test fails, the decision maker has to do the pairwise comparison again. The following example illustrates the consistency check of DM's preferences in Table 4.5.

<u>Consistency check:</u>

Find $Lamda$ such that $A \times W = Lamda \times W$

Given,

$$A = \begin{pmatrix} 1 & 8 & 6 & 8 & 8 \\ 1/8 & 1 & 1/6 & 1 & 1 \\ 1/6 & 6 & 1 & 6 & 6 \\ 1/8 & 1 & 1/6 & 1 & 1 \\ 1/8 & 1 & 1/6 & 1 & 1 \end{pmatrix} \qquad W = \begin{pmatrix} 0.572 \\ 0.056 \\ 0.260 \\ 0.056 \\ 0.056 \end{pmatrix}$$

$$\begin{pmatrix} 3.475 \\ 0.283 \\ 1.362 \\ 0.283 \\ 0.283 \end{pmatrix} = Lamda_{max} \begin{pmatrix} 0.572 \\ 0.056 \\ 0.260 \\ 0.056 \\ 0.056 \end{pmatrix}$$

$$Lamda_{max} = \text{average } \left(\frac{3.475}{0.572}, \frac{0.283}{0.056}, \frac{1.362}{0.260}, \frac{0.283}{0.056}, \frac{0.283}{0.056}\right)$$

$$Lamda_{max} = 5.2944$$

Consistency Index (CI) = $\dfrac{Lamda_{max} - n}{n-1}$ = 0.0736

Consistency Ratio (CR) = CI/RI (RI for n=4 is 1.11)

= 0.0736/1.11 = 0.0663

Since CR = 0.0663 <0.1, accept the pairwise comparison matrix.

Pros and cons of the preemptive and the non-preemptive GP approaches are given in Table 4.7.

Table 4.7: Pros and cons of different GP formulations

	Preemptive GP	Non-preemptive GP
Pros	Scaling is not required	Linear tradeoffs among objectives are allowed due to the pre-specified weights
	Preemptive priorities are easily obtained	Problem is easy to solve since it is converted to a single objective problem. All objective functions are optimized simultanously
Cons	Tradeoffs among objectives are not allowed since the approach does not capture the strength of preferences	Scaling is required due to the differences in units and magnitudes of objectives
	Problem is difficult and time consuming to solve since it is a sequencial optimization problem	Weights may be difficult and time consuming to obtain

4. 4 Numerical Example

We shall now illustrate the multi-objective strategic model for the global supply chain network design and the goal programming approaches. A global supply chain consists of three suppliers (K1, K2, K3), two manufacturing plants (M1, M2), two DCs (N1, N2), and three customer zones (C1, C2, C3), which are located in various locations around the world. There are two transportation links (U1, U2) available between each pair of facilities. There are two types of raw materials (i1, i2) and two types of finished products (j1, j2). A representation of the global supply chain is shown in Figure 4.4. The disruption risk scores for nodes (facilities) and links (transportation links) are determined using the disruption risk assessment procedure described in Chapter 3.

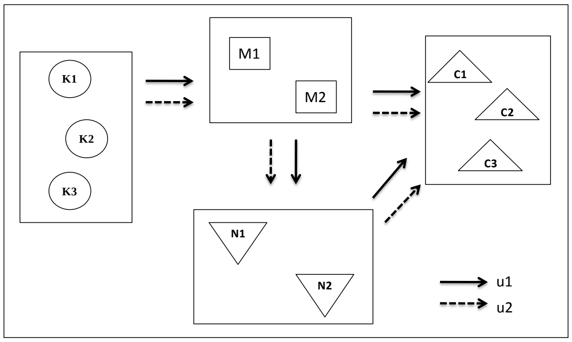


Figure 4.4: Supply chain problem for a numerical example

4.4.1 Illustrative data for the supply chain network model

We use the following data to illustrate the proposed supply chain network model.

Table 4.8: Suppliers and raw materials data

	K1 (Japan)		K2 (Thailand)		K3 (China)	
FSC(k)	100000		85000		70000	
VaR(k)	8.739		16.817		15.196	
	i1	**i2**	**i1**	**i2**	**i1**	**i2**
FSC(i,k)	20000	20000	17500	17500	15000	15000
CAP(i,k)	200000	200000	350000	350000	500000	500000
MIN(i,k)	20000	20000	35000	35000	50000	50000
MC(i,k)	10	12	9	11	8	10

Table 4.9: Forecasted demands data

	C1		C2		C3	
	j1	**j2**	**j1**	**j2**	**j1**	**j2**
D(j,c)	50000	50000	50000	35000	25000	30000
f(j,c)	0.9	0.9	0.9	0.9	0.9	0.9
SP(j,m,c)	450	450	550	550	450	450
SP(j,n,c)	500	500	600	600	500	500

Table 4.10: Plants and productions data

	M1		M2	
FSC(m)	100000		120000	
VaR(m)	12.033		9.524	
CAP(m)	250000		250000	
∅(m)	2.0%		3.2%	
∂(m)	3.0%		4.0%	
MIND	5000		5000	
	j1	**j2**	**j1**	**j2**
FSC(j,m)	20000	22000	25000	25000
CAP(j,m)	150000	100000	150000	100000
MIN(j,m)	30000	20000	30000	20000
PC(j,m)	15	20	16	21

Table 4.11: DCs and storage data

	N1		N2	
FSC(n)	100000		120000	
CAP(n)	2000000		2000000	
VaR(n)	6.475		4.947	
	j1	**j2**	**j1**	**j2**
FSC(j,n)	20000	28000	22000	30000
S (j)	8	8	8	8
SC(j,n)	2	2	2.5	2.5

Table 4.12: Data on transportation links between suppliers and plants

u	k	m	LT(u,k,m)	CAP(u,k,m)	MIN(u,k,m)	VaR(u,k,m)	FTC(u,k,m)
1	1	1	1	500000	50000	9.491	10000
1	1	2	1	500000	50000	9.491	10000
1	2	1	1	500000	50000	10.903	10000
1	2	2	1	500000	50000	10.903	10000
1	3	1	1	500000	50000	10.903	10000
1	3	2	1	500000	50000	10.903	10000
2	1	1	2	500000	50000	12.778	5000
2	1	2	2	500000	50000	12.778	5000
2	2	1	2	500000	50000	14.678	5000
2	2	2	2	500000	50000	14.678	5000
2	3	1	2	500000	50000	14.678	5000
2	3	2	2	500000	50000	14.678	5000

Table 4.13: Shipping cost of transportation link between suppliers and plants

i	u	k	m	TC(i,u,k,m)
1	1	1	1	3
1	1	1	2	3
1	1	2	1	2.4
1	1	2	2	2.4
1	1	3	1	2.1
1	1	3	2	2.1
1	2	1	1	1.5
1	2	1	2	1.5
1	2	2	1	1.2
1	2	2	2	1.2
1	2	3	1	1.05
1	2	3	2	1.05

i	u	k	m	TC(i,u,k,m)
2	1	1	1	3.6
2	1	1	2	3.6
2	1	2	1	3
2	1	2	2	3
2	1	3	1	2.7
2	1	3	2	2.7
2	1	1	1	1.8
2	1	1	2	1.8
2	1	2	1	1.5
2	1	2	2	1.5
2	1	3	1	1.35
2	1	3	2	1.35

Table 4.14: Data on transportation links between plants and DCs

u	m	n	LT(u,m,n)	CAP(u,m,n)	MIN(u,m,n)	VaR(u,m,n)	FTC(u,m,n)
1	1	1	1	200000	10000	5.995	3000
1	1	2	1	200000	10000	5.995	4000
1	2	1	1	200000	10000	5.995	4000
1	2	2	1	200000	10000	5.995	5000
2	1	1	2	200000	10000	9.238	1500
2	1	2	2	200000	10000	9.238	2000
2	2	1	2	200000	10000	9.238	2000
2	2	2	2	200000	10000	9.238	2500

Table 4.15: Shipping cost of transportation link between plants and DCs

j	u	m	n	TC(j,u,m,n)
1	1	1	1	8
1	1	1	2	10
1	1	2	1	10
1	1	2	2	12
1	2	1	1	4
1	2	1	2	5
1	2	2	1	5
1	2	2	2	6

j	u	m	n	TC(j,u,m,n)
2	1	1	1	8
2	1	1	2	10
2	1	2	1	10
2	1	2	2	12
2	2	1	1	4
2	2	1	2	5
2	2	2	1	5
2	2	2	2	6

Table 4.16: Data on transportation links between plants and customers

u	m	c	LT(u,m,c)	CAP(u,m,c)	MIN(u,m,c)	VaR(u,m,c)	FTC(u,m,c)
1	1	1	2	200000	2000	9.491	6000
1	1	2	2	200000	2000	9.491	6000
1	1	3	2	200000	2000	9.491	6000
1	2	1	2	200000	2000	9.491	7500
1	2	2	2	200000	2000	9.491	7500
1	2	3	2	200000	2000	9.491	7500
2	1	1	3	200000	2000	12.778	3000
2	1	2	3	200000	2000	13.857	3000
2	1	3	3	200000	2000	12.778	3000
2	2	1	3	200000	2000	13.857	4000
2	2	2	3	200000	2000	12.778	4000
2	2	3	3	200000	2000	13.857	4000

Table 4.17: Shipping cost of transportation link between plants and customers

j	u	m	c	TC(j,u,m,c)	j	u	m	c	TC(j,u,m,c)
1	1	1	1	30	2	1	1	1	30
1	1	1	2	30	2	1	1	2	30
1	1	1	3	30	2	1	1	3	30
1	1	2	1	36	2	1	2	1	36
1	1	2	2	36	2	1	2	2	36
1	1	2	3	36	2	1	2	3	36
1	2	1	1	16	2	2	1	1	16
1	2	1	2	16	2	2	1	2	16
1	2	1	3	16	2	2	1	3	16
1	2	2	1	18	2	2	2	1	18
1	2	2	2	18	2	2	2	2	18
1	2	2	3	18	2	2	2	3	18

Table 4.18: Data on transportation links between DCs and customers

u	n	c	LT(u,n,c)	CAP(u,n,c)	MIN(u,n,c)	VaR(u,n,c)	FTC(u,n,c)
1	1	1	1	100000	1000	8.263	3000
1	1	2	1	100000	1000	8.263	3000
1	1	3	1	100000	1000	7.193	3000
1	2	1	1	100000	1000	8.263	5000
1	2	2	1	100000	1000	8.263	5000
1	2	3	1	100000	1000	6.284	5000
2	1	1	2	100000	1000	12.778	1500
2	1	2	2	100000	1000	12.778	1500
2	1	3	2	100000	1000	11.124	1500
2	2	1	2	100000	1000	12.778	2000
2	2	2	2	100000	1000	12.778	2000
2	2	3	2	100000	1000	9.718	2000

Table 4.19: Shipping cost of transportation link between DCs and customers

j	u	n	c	TC(j,u,n,c)	j	u	n	c	TC(j,u,n,c)
1	1	1	1	5	2	1	1	1	5
1	1	1	2	5	2	1	1	2	5
1	1	1	3	5	2	1	1	3	5
1	1	2	1	7	2	1	2	1	7
1	1	2	2	7	2	1	2	2	7
1	1	2	3	7	2	1	2	3	7
1	2	1	1	2.5	2	2	1	1	2.5
1	2	1	2	2.5	2	2	1	2	2.5
1	2	1	3	2.5	2	2	1	3	2.5
1	2	2	1	3.5	2	2	2	1	3.5
1	2	2	2	3.5	2	2	2	2	3.5
1	2	2	3	3.5	2	2	2	3	3.5

The preemptive priority and non-preemptive weights, which are pre-determined by the decision maker, are summarized in Table 4.20. The preemptive priorities will be used in the P-GP formulation. The non-preemptive weights from the simple rating method and AHP will be used in the NP-GP formulation.

Table 4.20: Priorities and weights used in the P-GP and NP-GP models

Criteria	Preemptive Priority	Weights (from rating method)	Weights (from AHP)
Z1: Profit	#1	0.45	0.572
Z2: Unfulfilled Demand	#5	0.1	0.056
Z3: Delivery Time	#2	0.25	0.26
Z4: Disruption risk facility	#3	0.1	0.056
Z5: Disruption risk transportation	#4	0.1	0.056

The goal programming approach begins with finding the ideal values of the five objectives (maximum profit, minimum unfulfilled demand, minimum delivery time, minimum facility disruption risk, and minimum transportation disruption risk). The ideal solutions are obtained by optimizing each objective independently ignoring the other objectives. For instance, an ideal value for the profit is obtained by maximizing profit ignoring other objectives. Similarly, an ideal value for the facility disruption risk is obtained by minimizing facility disruption risk ignoring other objectives. The ideal values for profit, unfulfilled demand, delivery time to customer, facility disruption risk, and transportation risk, are given in Table 4.21. Note that except for profit, the other objectives are to minimize.

Table 4.21: Ideal values and Target values

Objectives	Ideal Values	Target values (0.5% from Ideal value)
Z1: Profit ($)	109,180,410	108,634,507.95
Z2: Unfulfilled demand (%)	0	0.50%
Z3: Delivery time	216000	217080
Z4: Disruption risk of facility	21.20	21.30
Z5: Disruption risk of transportation	18.77	18.86

Once an ideal value of each objective function has been determined, the decision maker will be asked to set the target values. In this example, we assume that the decision maker sets the profit target value at 99.5% of the ideal profit value($0.995 \times 109{,}180{,}410 = 108{,}634{,}507.95$), the unfulfilled demand target value at 0.5% (that is 99.5% of the forecasted demands must be fulfilled), the delivery time target value at 0.5% above the ideal delivery time value ($1.005 \times 216000 = 217080$), the facility disruption risk target value at 0.5% above the ideal facility disruption risk value ($1.005 \times 21.20 = 21.30$), and the transportation disruption risk target value at 0.5% above the ideal transportation disruption risk value ($1.005 \times 18.77 = 18.86$). The target values are summarized in the last column of Table 4.21. These target values are treated as goal constraints in the multi-criteria model. Next we present the results of supply chain network design decisions and supply chain performances of single objective models and multi-criteria models.

4.5 Discussion of Results

This section presents the results of supply chain network design decisions and supply chain performances from the multi-criteria models solved by Preemptive and Non-preemptive Goal Programming.

Table 4.22: Supply Chain Network Decisions from Goal Programming Techniques

Supply chain network design		P_GP	NP_GP (weights from rating method)	NP_GP (weights from AHP)
Suppliers	K1	No	Select	Select
	K2	No	No	No
	K3	Select	Select	Select
Plants	M1	Select	Select	Select
	M2	Select	Select	Select
DCs	N1	Select	No	Select
	N2	No	Select	No
Transportation links	U1	Select	Select	Select
	U2	Select	No	No
Direct shipment from plants to customers		No	No	No

Table 4.23: Supply Chain Network Performances from GP Techniques

Objective Function Value	Supply Chain Performance				
	Ideal Values	**Target Values**	**P_GP method**	**NP_GP (weights from rating method)**	**NP_GP (weights from AHP)**
Z1: Profit ($)	109,180,410	108,634,507.95	108,634,508 (achieved)	102,825,140 (not achieved by 5.35%)	104,802,140 (not achieved by 3.53%)
Z2: Unfulfilled Demand (%)	0%	0.50%	0% (achieved)	0% (achieved)	0% (achieved)
Z3: Delivery Time	216000	217080	264040 (not achieved by 21.63%)	240000 (not achieved by 10.56%)	240000 (not achieved by 10.56%)
Z4: Facility Disruption Risk	21.20	21.30	32.75 (not achieved by 53.76%)	27.10 (not achieved by 27.23%)	28.62 (not achieved by 34.37%)
Z5: Transportaion Disruption Risk	18.77	18.86	32.39 (not achieved by 71.74%)	24.30 (not achieved by 28.84%)	24.24 (not achieved by 28.53%)

From Tables 4.22 and 4.23, the P-GP solution suggests choosing supplier K3, plants M1 and M2, distribution center N1, using transportation link U2 to ship items among suppliers, plants, and DC facilities, and using transportation link U1 to hip items from DC to customer zones, as illustrated in Figure 4.5. The profit and the unfulfilled demand objectives are achieved. However, the delivery time to customers, the facility disruption risk, and the transportation disruption risk objectives are not achieved, differing by 21.63%, 53.76%, and 71.74% from the target values, respectively. Since profit is the most important, supply chain network design solution includes inexpensive facilities and transportation links. Raw materials are purchased from supplier K3, which has the lowest cost among the three suppliers. Most of the finished products are produced at plant M1 because its production costs are lower than those at plant M2. Similarly, DC N1 is selected, as it is less expensive to operate than DC N2. Transportation link U2 carries higher quantity of raw materials and finished products than the link U1. There is no direct shipment from plants to customers.

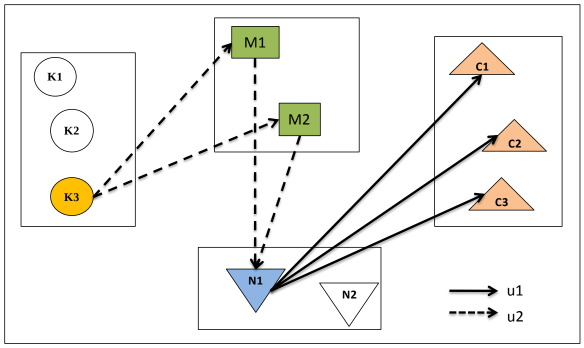


Figure 4.5: Supply Chain Network Design from the P-GP

The NP-GP solution (with weights from the simple rating method) suggests choosing suppliers K1 and K3, plants M1 and M2, distribution center N2, and using transportation link U1. Direct shipment from plants to customers is not selected. Finished products are distributed to customers via DC N2, (see Figure 4.6). For this solution, the unfulfilled demand is achieved. However, profit, delivery time, facility disruption risk, and transportation disruption risk objectives are not achieved, differing by 5.35%, 10.56%, 27.23%, and 28.84% from the target values, respectively. Notice that this solution has lower facility and transportation disruption risk values than the P-GP solution. However, the profit value is decreased.

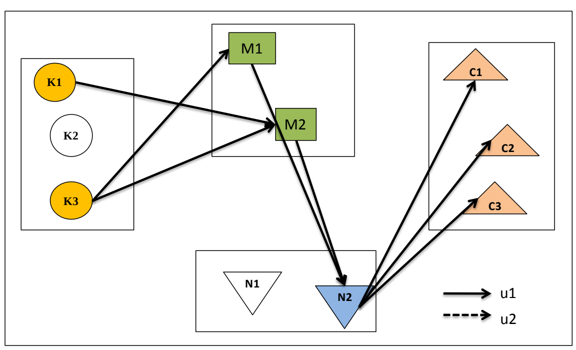


Figure 4.6: Supply Chain Network Design from the NP-GP (weights from simple rating)

The NP-GP solution (with weights from AHP) suggests choosing suppliers K1 and K3, plants M1 and M2, distribution center N1, and using transportation link U1. Direct shipment from plant to customers is not allowed. Finished products are distributed to customers via DC N1, (see Figure 4.7). For this network design, the unfulfilled demand is achieved. However, profit, delivery time, facility disruption risk, and transportation disruption risk goals are not achieved, differing by 3.53%, 10.56%, 34.37%, and 28.53% from the target values, respectively.

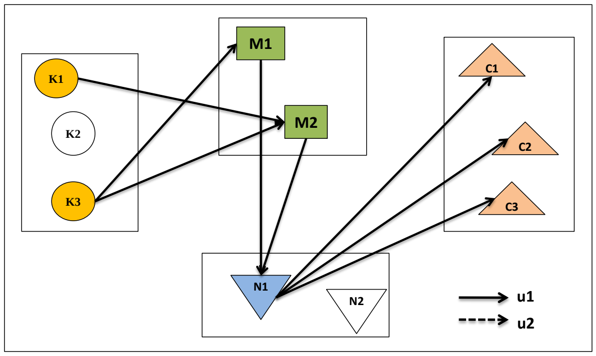


Figure 4.7: Supply Chain Network Design from the NP-GP (weights from AHP)

From the numerical example, we observe the following:

i) The NP-GP solution has lower disruption risk objective values than the P-GP solution. This is because P-GP is a sequential optimization model. The problem is solved sequentially with respect to the decision maker's order of preference. As the profit objective is the most important, the model selects facilities and transportation links that are inexpensive (e.g., facilities K3, N1, and link U2), resulting in high disruption risks. On the other hand, NP-GP is a single objective optimization model, and all criteria are solved simultaneously with relative weights assigned to them. The NP-GP solutions contain low-disruption risk facilities and transportation links (e.g., facilities K1, N2, and link U1). Thus, it is likely that the company will spend fewer resources to prepare and mitigate potential disruptions, but at a loss in profit.

ii) Between the NP-GP solutions, the NP-GP solution (weights from rating method) has a lower facility disruption risk value than the other. This is because the disruption risk weight values from the simple rating method are higher than the values from AHP.

iii) None of the GP solutions could achieve all the target values. In other words, a decision maker has to consider the tradeoffs between different solutions. A decision maker can evaluate how much profit the company is willing to compromise in order to reduce the disruption risk values or improve the robustness of the supply chain network.

iv) We can study the impact of the supply chain disruption on each network design by examining the disruption risk scores. In the P-GP solution, supplier K3 and plant M1 have very high disruption risk values compared to the other facilities due to high occurrence of risk events and a lack of risk monitoring and risk mitigation practices at these two locations. Hence, the company should closely monitor supplier K3 and plant M1 and prepare mitigation strategies. Supplier K3 is prone to flood, which is quite predictable. However, it occurs frequently. Supplier's suppliers are located in a disaster prone area. In addition, the supplier is located in a developing country where economic instability is high and risk management practices are not fully implemented. A company should establish risk mitigation strategies by having a backup supplier or by carrying extra inventory at plants to cope with the supply disruption. Plant M1 is also prone to flood, which occurs almost every year. The facility is located in a disaster prone area and the country is under a political instability. Disaster preparedness and recovery plan are not yet implemented. A company may develop a contingency plan to relocate its production to other plant facilities in order to reduce risk from a possible plant disruption. Furthermore, the company should also pay attention to the transportation link U2 from supplier K3 to all plants. Risk mitigation strategies, such as choosing alternate transportation links and risk monitoring, should help address plausible disruptions from unpredictable events, long transportation lead-times, and a large number of transshipments.

4.6 Comparison of the supply chain network design results

The P-GP and NP-GP models provide different solutions and levels of goal achievement. In order to compare the three supply chain design alternatives and their trade-offs, we use the *value path approach* (VPA) to display objective function values of different solutions. VPA has been proposed by Schilling et al. (1983) and is one the most efficient ways to demonstrate the tradeoffs among conflicting objectives visually.

From a set of solutions, the VPA starts with determining the best value corresponding to each objective function. The best value corresponding to a maximization objective is the highest value among all alternatives, while the best value corresponding to a minimization objective is the lowest value among all alternatives. Next, the best value is scaled to 1, while others are scaled to a value greater than 1. The larger the scaled value, the worse a method performs on that objective. A scaled value corresponding to a maximization objective is determined by dividing the best value by the achieved value, while a scaled value corresponding to a minimization objective is determined by dividing the achieved value by the best value. From Table 4.24, the best values for profit and demand fulfillment, which are maximization objectives, are 108,634,507.95 and 100%. The best values for delivery time to customers, facility disruption risk, and transportation disruption risk, which are minimization objectives, are 240000, 27.10, and 24.24, respectively. Note that we replace the unfulfilled demand objective with the demand fulfillment to avoid a computational error. For the P-GP method, the achieved values for profit, demand fulfillment, delivery time to customers, facility disruption risk, and transportation disruption risk are 108634507.95, 100, 264040, 32.75, and 32.39, respectively. Hence, the scaled objective values corresponding to the P-GP solution are (108634507.95/108634507.95), (100/100), (264040/240000), (32.75/27.10), and (32.39/24.24), respectively. For the NP-GP method, with weights from the rating method, the achieved values for profit, demand fulfillment, delivery time to customers, facility disruption risk, and transportation disruption risk are 102825140, 100, 240000, 27.10, and 24.30, respectively. Hence, the scaled objective values corresponding to the NP-GP solution are obtained as (108634507.95/102825140), (100/100), (264040/240000), (32.75/27.10), and (32.39/24.30), respectively. Table 4.24 shows the objective values with their ratios in parentheses for the three solutions from the GP methods.

Figure 4.8 shows the value path of three supply chain network design alternatives. The horizontal axis represents profit, demand fulfillment, delivery time to customers, facility disruption risk, and transportation disruption risk. The vertical axis represents the ratios of the objective values.

Table 4.24: Summary of Objective Function Values and the Scaled Values

Objective Function Value	P_GP method	NP_GP (weights from rating method)	NP_GP (weights from AHP)	Best Value
Z1: Profit ($)	108,634,508 (1.000)	102,825,140 (1.056)	104,802,140 (1.037)	108,634,508 (1.000)
Z2: Demand Fulfillment (%)	100 (1.000)	100 (1.000)	100 (1.000)	100 (1.000)
Z3: Delivery Time	264040 (1.100)	240000 (1.000)	240000 (1.000)	240000 (1.000)
Z4: Disruption risk facility	32.75 (1.208)	27.10 (1.000)	28.62 (1.056)	27.10 (1.000)
Z5: Disruption risk transportation	32.39 (1.336)	24.30 (1.002)	24.24 (1.000)	24.24 (1.000)

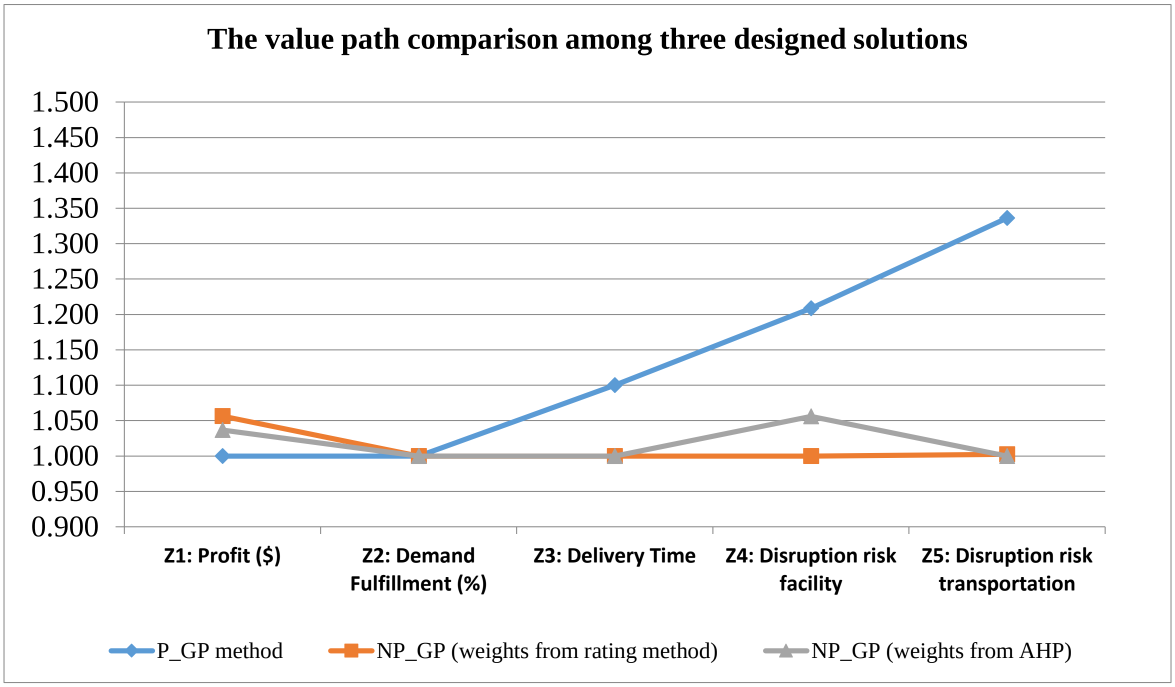


Figure 4.8: The Value Path Comparison for Supply Chain Network Design Solutions

The output of the VPA can be used to determine dominated and non-dominated solutions. If the value path of one solution is above another, then the solution is a dominated solution. If value paths of two solutions cross each other, then these solutions do not dominate each other. From Figure 4.8, none of the three solutions are dominated. VPA can be used to perform a visual tradeoff analysis among the different solutions. For example, the NP-GP solution (with weights from rating method) does 10% better than the P-GP solution on delivery time to customers, 20.8% better on the facility disruption risk, and 33.6% better on the transportation disruption risk, but at the cost of 5.6% in lower profit.

4.7 Alternative approach to solve the multi-criteria mathematical problem (MCMP)

Goal programming technique used in Section 4.3 to solve MCMP requires completely pre-specified preference from a decision maker. In addition, the non-preemptive goal programming (NP-GP) assumes that a decision maker's utility function is linear. In practice, defining preference numerically could be difficult. Another MCMP approach, called an interactive method, can be used to overcome this issue. A interactive method does not require pre-specified preference, but relies on the progressive articulation of preferences by a decision maker (Masud & Ravindran, 2008). The authors provide a general procedure for an interactive method as follows:

Step1: Find an efficient solution

Step2: Interact with a decision maker to obtain response to the obtained solution

Step3: Repeat steps 1 and 2 until satisfaction is achieved or until some termination criterion is met.

We apply the interactive method to our numerical example. The result is presented below:

Step1: Generate a set of efficient solutions using six different weight sets, as shown in Table 4.25. Note that the first 5 weight sets correspond to individual optimization of each objective, ignoring other objectives. Weight set 6 gives equal weights to all objectives.

Table 4.25: Weight sets to generate efficient solutions

Criteria	Weight set 1	Weight set 2	Weight set 3	Weight set 4	Weight set 5	Weight set 6
Z1: Profit	0.96	0.01	0.01	0.01	0.01	0.2
Z2: Demand fulfillment	0.01	0.96	0.01	0.01	0.01	0.2
Z3: Delivery	0.01	0.01	0.96	0.01	0.01	0.2
Z4: Facility disruption risk	0.01	0.01	0.01	0.96	0.01	0.2
F5: Transportation disruption risk	0.01	0.01	0.01	0.01	0.96	0.2
Sum	1.00	1.00	1.00	1.00	1.00	1.00

The objective function values and the corresponding network design for each weight set are shown in Tables 4.26 and 4.27.

Table 4.26: Objective function values correspond to each weight set

Criteria	Weight set 1	Weight set 2	Weight set 3	Weight set 4	Weight set 5	Weight set 6
Z1: Profit ($)	108,575,910.00	102,825,140.00	102,482,660.00	87,564,640.00	87,564,640.00	102,514,740.00
Z2: Unfulfilled demand (%)	0.00	0.00	0.00	0.00	0.00	0.00
Z3: Delivery time	240000	240000	240000	480000	480000	240000
Z4: Facility risk	32.75	27.61	27.10	22.15	22.15	27.30
Z5: Transportation risk	31.93	24.48	24.03	19.72	19.72	24.17

Table 4.27: Network design corresponding to each weight set

Supply chain component	Weight set 1	Weight set 2	Weight set 3	Weight set 4	Weight set 5	Weight set 6
Suppliers	K3	K1, K3	K1, K2, K3	K1, K3	K1, K3	K1, K2, K3
Plants	M1, M2	M1, M2	M1, M2	M1, M2	M1, M2	M1, M2
DCs	N1	N2	N2	-	-	N1, N2
Transportation links	U1, U2	U1	U1, U2	U1	U1	U1, U2
Direct shipment from plants to customers	No	No	No	Yes	Yes	No

From Table 4.27, we obtain 5 different efficient designs. The first design is from the weight set 1, which provides the highest profit ($108,575,910), but it also provide the highest disruption risks (32.75 and 31.93). The second design is from the weight sets 4 and 5, which provide the lowest disruption risks (22.15 and 19.72), but it also provides the lowest profit ($87,564,640). The other three designs are from the weight sets 2, 3, and 6, which have objective function values lie between those of designs 1 and 2.

Step2: Interact with the decision maker to choose the most preferred solution. Suppose a decision maker prefers the three design solutions from the weight sets 2, 3, and 6 due to the similarity in their profit and disruption risk values.

Step3: We generate a new set of efficient solutions around those three design solutions. Based on the weight sets 2, 3, and 6, we vary the weight values as shown in Table 4.28 and re-optimize the NP-GP model. The results are summarized in Table 4.29.

Table 4.28: Weight sets to generate efficient solutions

Criteria	Weight set 2_1	Weight set 3_1	Weight set 6_1
Z1: Profit ($)	0.21	0.21	0.4
Z2: Unfulfilled demand (%)	0.76	0.01	0.1
Z3: Delivery	0.01	0.76	0.1
Z4: Facility risk	0.01	0.01	0.2
Z5: Transportation risk	0.01	0.01	0.2

Table 4.29: Objective function values correspond to each weight set

Criteria	Weight set 2_1	Weight set 3_1	Weight set 6_1
Z1: Profit ($)	107,949,240.00	107,949,240.00	102,825,140.00
Z2: Unfulfilled demand (%)	0.00	0.00	0.00
Z3: Delivery time	240000	240000	240000
Z4: Facility risk	31.72	31.72	27.10
Z5: Transportation risk	30.33	30.33	24.03

Table 4.30: Network design corresponding to each weight set

Supply chain component	Weight set 2_1	Weight set 3_1	Weight set 6_1
Suppliers	K3	K3	K1, K3
Plants	M1, M2	M1, M2	M1, M2
DCs	N1	N1	N2
Transportation links	U1, U2	U1, U2	U1
Direct shipment from plants to customers	No	No	No

From Table 4.29, there are 2 efficient design solutions. The first solution is from the weight sets 2_1 and 3_1. The profit is $107,949,240, unfilled demand is 0%, delivery time is 240000, facility disruption risk is 31.72, and transportation link disruption risk is 30.33. Table 4.30 presents the network design corresponding to each weight set. The supply chain network configurations from the weight sets 2_1 and 3_1 are the same as the design from weight set 1. Another solution is from the weight set 6_1, which is the same as the solution from the NP-GP solution with weights from the simple rating method. Next, we repeat step 2.

Step2: Interact with the decision maker to choose the preferred solution. Suppose the decision maker chooses the design from weight set 6_1 and satisfies with this solution. We stop the interaction process.

4.8 Conclusion

Supply chain network design decisions such as supplier selection, facility location, production and distribution planning, and transportation network design, are long-term decisions. They cannot be changed frequently and any changes may cause high impact to the whole network. Without considering disruption risk of a supply chain, a supply chain network design that relies heavily on maximizing profit and customer satisfaction may create a network characterized by high disruption risk. Hence, disruption risk should be incorporated when making supply chain strategic decisions in addition to profit and customer satisfaction.

This chapter illustrates how to incorporate disruption risks when making supply chain strategic decisions. We apply the disruption risk assessment framework proposed in Chapter 3, which quantifies disruption risks of supply chain components based on risk events, vulnerability, and risk management practice factors. The use of goal programming (GP) to handle the multiple and conflicting objectives of the global supply chain network design allows decision makers to participate in the solution process. In addition, a decision maker can generate various solutions by using different GP techniques. The illustrative example shows that the robustness of the supply chain network can be improved by incorporating disruption risk in the supply chain network.

Chapter 5

Multi-Period, Tactical Model for Global Supply Chain Network incorporating Disruption Risk

In the previous chapter, we formulated a multi-criteria supply chain network design optimization model incorporating disruption risk in the design criteria. Even though risk minimization is considered when making the strategic network design decisions, risks still exist. A disruption at a supply chain component may occur at any time during the planning horizon. In this chapter, we formulate a mathematical model to support a multi-period tactical model for supply chain management based on the strategic decisions taken during the design phase. The tactical model provides optimal supply chain management decisions assuming no disruption over the planning horizon. The optimal solution represents a disruption-free scenario under "normal" operation, which will be used for a vulnerability analysis and a risk mitigation analysis in Chapter 6. The tactical supply chain network model is the third module in our disruption risk management framework, as shown in Figure 5.1.

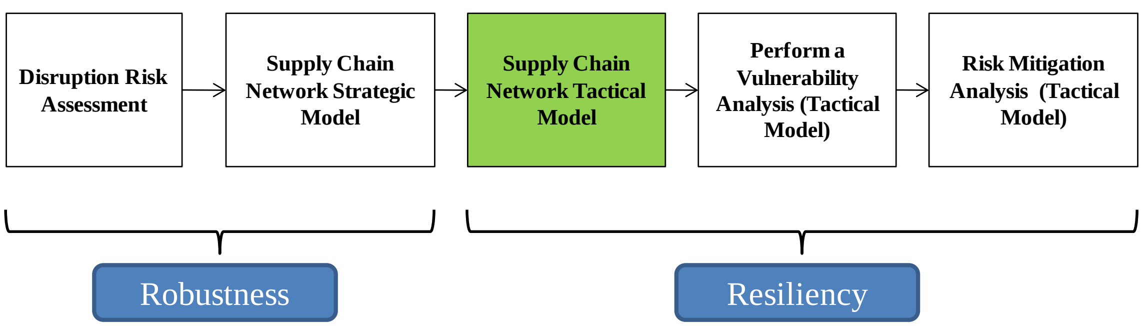


Figure 5.1: Supply Chain Network Tactical Model in a Disruption Risk Management Framework for a Global Supply Chain Network

Once the suppliers, plants and distribution center locations, and the transportation links have been selected using the strategic model in Chapter 4, a company wants to determine at a tactical level the supply chain planning decisions that include raw material purchasing plan, production plan, distribution plan, and inventory policies. These tactical decisions are determined to achieve maximum profit. The tactical model differs from the strategic model as follows:

i) The strategic model supports long-term design decisions, while the tactical model supports medium-term planning decisions. The strategic decision primarily refers to the supply chain network configuration. The tactical decision focuses on the product flow allocation and distribution.

ii) The strategic model is a single-period model, but the tactical model is a multi-period model. Once the strategic supply chain network configuration is decided, it will be used for developing the tactical decisions.

iii) The strategic model aims to achieve supply chain network profit, customer satisfaction, and disruption risk objectives, while the tactical model aims to maximize profit. The disruption risk and the delivery time objectives are not calculated at this level because the strategic decision has already considered the disruption risk. The demand fulfillment is considered as constraints.

iv) The strategic model considers both fixed cost and variable cost, while the tactical model focuses on operating cost only.

v) The strategic model provides a supply chain network structure decision, while the tactical model provides a purchasing plan, a production plan, and a distribution plan.

vi) The strategic model does not consider inventory, while the tactical model does.

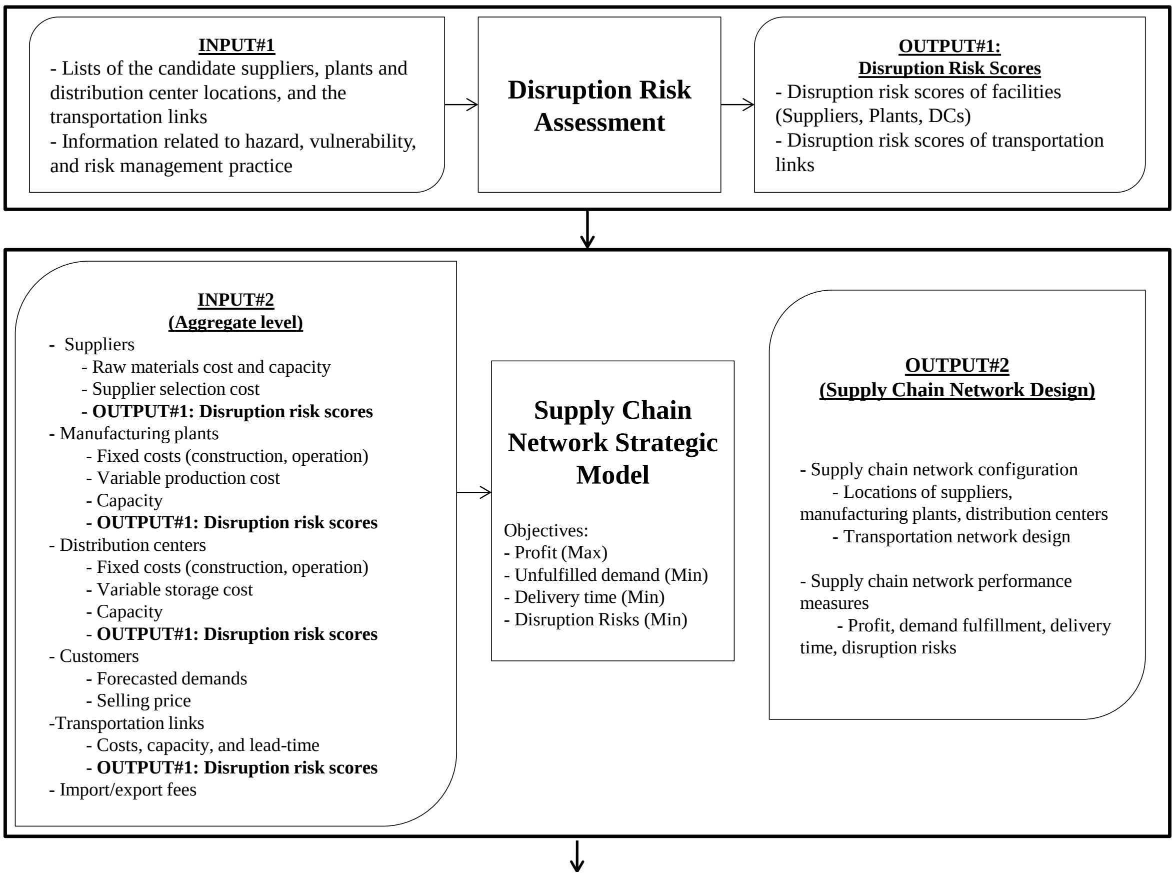
vii) From a risk management perspective, the strategic model improves a supply chain network's robustness by incorporating disruption risk as one of the objectives, while the tactical model facilitates a supply chain network operation's resiliency improvement through vulnerability and risk mitigation analysis, which will be discussed in Chapter 6.

The tactical model formulation in this research is similar to others in the literature, however the use of binary parameter to incorporate a supply chain component disruption at the supply chain tactical level provides contribution to the supply chain disruption study. Table 5.1 summarizes the differences between the strategic model and the tactical model.

Table 5.1: Differences between the strategic model and the tactical model

Differences between strategic and tactical models	Strategic Model	Tactical Model
(1) Planning horizon	Long-term (years)	Short-term (months, quarters)
(2) Time period	Single period	Multiple periods
(3) Model objectives	- Maximize profit, - Maximize customer satisfaction (demand fulfillment, delivery time), - Minimize disruption risk (facility, transportation link)	- Maximize profit, - Demand fulfillment is considered as constraint
(4) Cost function	Fixed cost and variable cost of construction, operation, procurement, production, storage, transportation, cross-sourcing	Variable cost of procurement, production, storage, inventory, transportation, cross-sourcing
(5) Outputs	- Supply chain network structure (selection of suppliers, plant locations, DC locations, and transportation links) - Supply chain performance	- Optimal raw materials purchasing plan, production plan, distribution plan, and inventory policy - Supply chain performance
(6) Inventory	Not included	Included
(7) Risk management	Enhance robustness of the supply chain network structure	Facilitate resiliency improvement of the supply chain network operation

In the tactical model formulation, the optimal decisions and the objective values from the strategic model will be used as inputs for the tactical model. Figure 5.2 presents inputs, outputs, and objectives of the supply chain network strategic model and the tactical model to show how the two models interact with each other. Using strategic decision variables as given tactical parameters, the number of binary decision variables in the tactical model is reduced. For example, if a facility or a transportation link has already been chosen in the strategic model, it remains open for the entire planning horizon in the tactical model. Table 5.2 provides a complete description of the relationship between the strategic decision variables and the tactical decision variables.



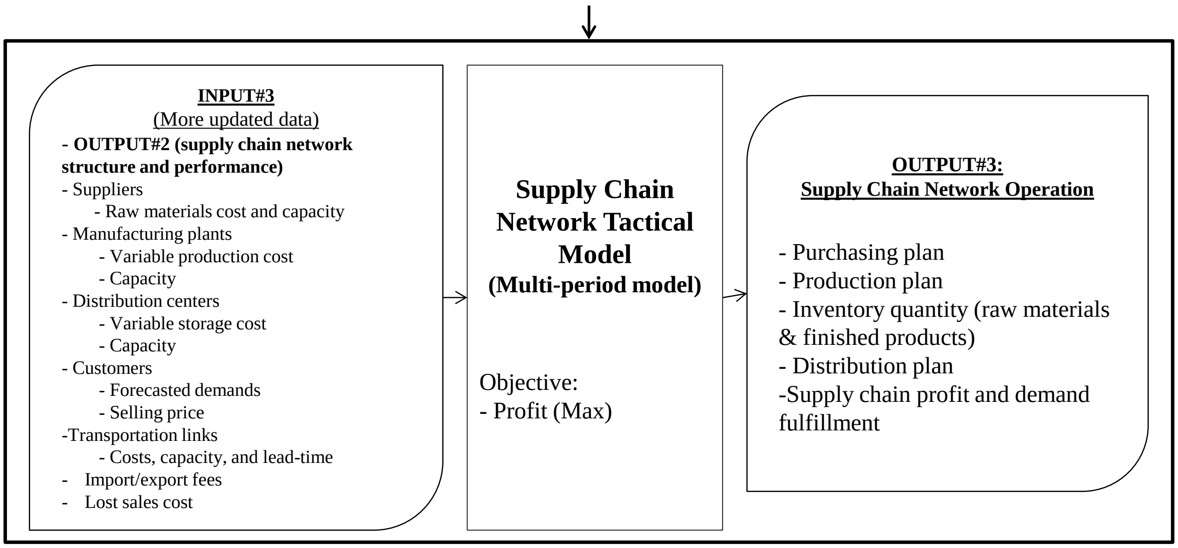


Figure 5.2: Strategic and Tactical Models Inputs, Outputs, and Objectives

Table 5.2: Relationship between Strategic Output and Tactical Input

Strategic Decision Variable (Unknown)	Tactical Input Parameter (Known)
(1) Supplier selection If X_{ik} = 1, raw material i is purchased from supplier k If X_{ik} = 0, raw material i is not purchased from supplier k	When X_{ik} =1: X_{ikt} = 1, raw material i can be purchased from supplier k in period t (t = 1,…, T) When X_{ik} =0: X_{ikt} = 0, for all t (t = 1,…, T)
(2) Plant selection If X_{jm} = 1, finished product j is produced at plant m If X_{jm} = 0, finished product j is not produced at plant m	When X_{jm} = 1: X_{jmt} = 1, finished product j can be produced at plant m in period t (t = 1,…, T) When X_{jm} = 0: X_{jmt} = 0, for all t (t = 1,…, T)
(3) DC selection If X_n = 1, DC n is chosen, If X_n = 0, DC n is not chosen	When X_n = 1: X_{nt} = 1, DC n can be used in period t (t = 1,…, T) When X_n = 0: X_{nt} = 0, for all t (t = 1,…, T)
(4) Transportation link selection If X_{ufd} = 1, a transportation link u between facilities f and d is chosen, If X_{ufd} = 0, a transportation link u between facilities f and d is not chosen	When X_{ufd} = 1: X_{ufdt} = 1, transportation link u between facilities f and d can be used in period t (t = 1,…, T) When X_{ufd} = 0: X_{ufdt} = 0, for all t (t = 1,…, T)

5.1 Supply Chain Tactical Model Assumptions

- Forecasted demand of finished products at each customer zone and related information such as costs and capacity for the tactical level decisions are available. In addition, we do not consider the time value of money.
- Initial inventories of raw materials, finished products at plants and customer zones, and ending inventories are known parameters.
- Disruption does not occur during the planning horizon.
- Backordering is not allowed. Unfulfilled demand is penalized by a lost sale cost. The lost sales cost is the opportunity cost of the profit margin foregone by the shortage plus the cost of losing customer goodwill due to the shortage. Profit margin is an estimated difference between unit price and unit cost. Customer goodwill is used to inflate a stock out cost, which may be underestimated by a decision maker. However, customer goodwill is intangible and difficult to determine.

Section 5.2 provides a linear programming model formulation of the tactical model. The parameters and decision variables in the tactical model are similar to those in the strategic model, but include time periods. Therefore, most of the notation in the tactical model will be similar to the notation in the strategic model. We list only the additional parameters and decision variables needed in the tactical model.

5.2 Mathematical Formulation

Additional index set

t Time period ($t = 1, 2, \ldots, T$)

Additional parameters

X_{ikt} = 0 or 1 depending on whether raw material i can be purchased from supplier k

X_{jmt} = 0 or 1 depending on whether finished product j can be produced at plant m

X_{nt} = 0 or 1 depending on whether DC n can be used

X_{ufdt} = 0 or 1 depending on whether transportation link u between facilities f and d can be used

LC_{jct} Unit lost sales cost of finished product j at customer c in period t ($)

HC_{ft} Inventory holding cost per space unit at facility f in period t $(f \in M \cup N \cup C)$ ($/space unit)

$InitRM_{im}$ Initial inventory of raw material i at plant m (unit)

$InitFG_{jf}$ Initial inventory of finished product j at facility f $(f \in M \cup N \cup C)$ (unit)

$EndRM_{im}$ Ending inventory of raw material i at plant m (unit)

$EndFG_{jf}$ Ending inventory of finished product j at facility f $(f \in M \cup N \cup C)$ (unit)

LT_{ufd} Lead-time between facilities f and d by transportation link u

$(f \in K \cup M \cup N,\ d \in M \cup N \cup C)$

Decision Variables

Q_{pufdt} Quantity of item p shipped from origin facility f to destination facility d via transportation link u in period t

Y_{jmt} Quantity of finished product j produced at plant m in period t

d_{jct} Demand fulfillment of finished product j for customer c in period t

W_{jct} Unfulfilled demand of finished product j for customer c in period t

RM_{imt} Quantity of raw material i inventory at plant m at the end of period t

FG_{jft} Quantity of finished product j inventory at facility f in period t $(f \in M \cup N \cup C)$

Objective Function

- <u>Gross Profit</u>

The supply chain tactical decisions are made to maximize the supply chain profit. To determine the gross profit at the tactical level, we consider the revenue from sales less the variable costs of raw materials, production, operating cost at distribution center, shipping, inventory, cross sourcing, and lost sales cost. Fixed costs (e.g. construction cost, fixed selection cost, fixed operating cost, fixed transportation cost) are excluded from the tactical model due to the fact that facilities and transportation links have already been selected at the strategic level. In addition, those fixed costs are incurred in the supply chain network regardless of the quantities of items purchased, produced or shipped.

$$\begin{aligned} Gross\ Profit = {} & Revenue\ from\ sales \\ & - (Raw\ material\ cost + Production\ cost + Distribution\ center\ cost \\ & + Shipping\ cost + \ Inventory\ cost + Cross\ sourcing\ cost \\ & + Lost\ sales\ cost) \end{aligned} \tag{5.1}$$

Each component of the revenues and costs relevant to the supply chain operations are calculated as follows:

- <u>Sales revenue</u>

Sales revenue may come from direct shipment from plants or shipment from the distribution centers to the customer zones. The first component represents sales revenue from the plants, while the second component represents sales revenue from the distribution centers.

$$= \left(\sum_{t\in T}\sum_{c\in C}\sum_{m\in M}\sum_{j\in J} SP_{jmct} \times \sum_{u\in U_{umc}} Q_{jumct}\right) + \left(\sum_{t\in T}\sum_{c\in C}\sum_{n\in N}\sum_{j\in J} SP_{jnct} \times \sum_{u\in U_{unc}} Q_{junct}\right)$$

- Raw material cost

Raw material cost is the product of the amount of raw materials purchased and the unit cost, as shown in the following expression:

$$= \sum_{t\in T}\sum_{k\in K}\sum_{i\in I} MC_{ikt} \times \sum_{m\in M}\sum_{u\in U_{km}} Q_{iukmt}$$

- Production cost

A total variable production cost is the total amount of finished products produced multiplied by unit production cost, as shown in the following expression:

$$= \sum_{t\in T}\sum_{m\in M}\sum_{j\in J} PC_{jmt} \times Y_{jmt}$$

- Distribution center cost

A total variable distribution center cost depends on the space utilization. It is the total number of finished products handled at a DC multiplied by the unit space cost, as shown in the following expression:

$$= \sum_{t\in T}\sum_{n\in N}\sum_{j\in J} SC_{jnt} \times S_j \times \sum_{m\in M}\sum_{u\in U_{mn}} Q_{jumn(t-LT_{umn})}$$

$Note: Q_{jumnt} = 0\ for\ all\ (t - LT_{umn}) \leq 0$

- Shipping cost

A total variable shipping cost is the sum of the shipping cost between the suppliers and plants, shipping cost between the plants and DCs, shipping cost between the DCs and customer zones, and shipping cost between the plants and customer zones, as shown in the following expression:

$$Shipping\ cost = \sum_{t\in T}\sum_{u\in U_{ukm}}\sum_{m\in M}\sum_{k\in K}\sum_{i\in I} TC_{iukmt} \times Q_{iukmt}$$

$$+ \sum_{t\in T}\sum_{u\in U_{umn}}\sum_{n\in N}\sum_{m\in M}\sum_{j\in J} TC_{jumnt} \times Q_{jumnt}$$

$$+\sum_{t\in T}\sum_{u\in U_{unc}}\sum_{c\in C}\sum_{n\in N}\sum_{j\in J}TC_{junct}\times Q_{junct}$$

$$+\sum_{t\in T}\sum_{u\in U_{umc}}\sum_{c\in C}\sum_{m\in M}\sum_{j\in J}TC_{jumct}\times Q_{jumct}$$

- Inventory cost

A total inventory cost includes cost of holding raw materials and finished products inventory at the plants, cost of holding finished products inventory at the DCs, and cost of holding finished products inventory at the customer zones, as shown in the following expression:

$$Inventory\ cost = \sum_{t\in T}\sum_{m\in M}HC_{mt}\left(\sum_{i\in I}S_iRM_{imt} + \sum_{j\in J}S_jFG_{jmt}\right)$$

$$+\sum_{t\in T}\sum_{n\in N}HC_{nt}\left(\sum_{j\in J}S_jFG_{jnt}\right)$$

$$+\sum_{t\in T}\sum_{c\in C}HC_{ct}\left(\sum_{j\in J}S_jFG_{jct}\right)$$

- Lost sales cost

Since backordering is not allowed, an unfulfilled demand is penalized with a lost sale cost, as shown in the following expression:

$$=\sum_{t\in T}\sum_{c\in C}\sum_{j\in J}LC_{jct}(W_{jct})$$

- Cross-sourcing cost

Cross-sourcing cost includes an import fee applied to raw materials purchased from global suppliers and an export fee applied to finished products shipped from plants to customers, as shown in the following expression:

$$= \left[\sum_{t\in T}\sum_{m\in M}\emptyset_{mt}\sum_{k\in K}\sum_{i\in I}MC_{ikt}\sum_{u\in U_{km}}Q_{iukmt}\right] + \left[\sum_{t\in T}\sum_{m\in M}\partial_{mt}\sum_{c\in C}\sum_{j\in J}SP_{jct}\sum_{u\in U_{mc}}Q_{jumct}\right]$$

Model constraints

1. At suppliers:

1.1. Raw material capacity constraint: The amount of raw material i purchased from supplier k in period t must exceed the minimum order quantity, but it cannot exceed the supplier's capacity.

$$MIN_{ikt}X_{ikt} \leq \sum_{m\in M}\sum_{u\in U_{km}} Q_{iukmt} \leq CAP_{ikt}X_{ikt} \qquad \forall\, i,k,t \qquad (5.2)$$

2. At the plants

2.1. Production capacity constraint: The amount of product j produced at plant m in period t must exceed the minimum production size, but cannot exceed the plant's production capacity.

$$MIN_{jmt}X_{jmt} \leq Y_{jmt} \leq CAP_{jmt}X_{jmt} \qquad \forall\, j,m,t \qquad (5.3)$$

2.2. Storage capacity constraint: The amount of raw materials and finished products inventory are limited by the available storage space of plant ($SPACE_{mt}$), where S_i and S_j represent the space required to store one unit of raw material i and finished product j, respectively.

$$\left(\sum_{i\in I} S_i RM_{imt}\right) + \left(\sum_{j\in J} S_j FG_{jmt}\right) \leq SPACE_{mt} \qquad \forall\, m,t \quad (5.4)$$

2.3. Raw material inventory flow balancing constraint: The inventory of raw material i at the end of period t is determined by the inventory carried over from the previous time period plus any incoming material from suppliers minus the amount that is used in production in period t.

$$RM_{imt} = RM_{im(t-1)} + \sum_{k\in K}\sum_{u\in U_{km}} Q_{iukm(t-LT_{ukm})} - \sum_{j\in J} b_{ij}\, Y_{jmt} \qquad \forall i,m,t \quad (5.5)$$

$Note: Q_{iukmt} = 0, for\ all\ (t - LT_{ukm}) \leq 0$

2.4. Ending inventory constraint (for initializing the inventory for the next planning cycle)

$$RM_{imt} = EndRM_{im} \qquad \forall i,m,t = T \qquad (5.6)$$

2.5. Finished product inventory flow balancing constraint: The inventory of finished product j at the end of period t is determined by the inventory carried over from the previous time period plus the amount produced and minus the amount that is shipped out to DCs and customers.

$$FG_{jmt} = FG_{jm(t-1)} + Y_{jmt} - \sum_{n\in N}\sum_{u\in U_{mn}} Q_{jumnt} - \sum_{c\in C}\sum_{u\in U_{mc}} Q_{jumct} \qquad \forall j,m,t \qquad (5.7)$$

2.6. Ending inventory constraint (for initializing the inventory for the next planning cycle)

$$FG_{jmt} = EndFG_{jm} \qquad \forall j,m,t = T \qquad (5.8)$$

2.7. Raw material and finished product balancing constraint: This ensures that the quantity of finished products produced in period t is limited by the availability of raw materials:

$$\sum_{j\in J} b_{ij}\, Y_{jmt} \leq RM_{im(t-1)} + \sum_{k\in K}\sum_{u\in U_{km}} Q_{iukm(t-LT_{ukm})} \qquad \forall i,m,t \qquad (5.9)$$

$Note: Q_{iukmt} = 0, for\ all\ (t - LT_{ukm}) \leq 0, RM_{imt} = 0, for\ all\ (t-1) \leq 0$

2.8. Outbound transportation constraint: To ensure that an outbound shipping from plant to customers and DCs cannot exceed the available finished products in period t:

$$\sum_{n\in N}\sum_{u\in N_{mn}} Q_{jmnut} + \sum_{c\in C}\sum_{u\in N_{mc}} Q_{jumct} \;\le\; Y_{jmt} + FG_{jm(t-1)} \qquad \forall j,m,t \qquad (5.10)$$

3. At the DCs

3.1. Storage capacity constraint: To ensure that incoming finished products and inventory do not exceed the available space ($SPACE_{nt}$):

$$\sum_{j\in J} S_j\left(FG_{jn(t-1)} + \sum_{n\in M}\sum_{u\in N_{mn}} Q_{jmnu(t-LT_{umn})}\right) \le\; SPACE_{nt}X_{nt} \qquad \forall n,t \quad (5.11)$$

3.2. Finished product inventory flow balancing constraint: The inventory of finished product j at the end of period t is determined by the inventory carried over from the previous time period plus the amount received from plants less the amount that is shipped to the customers.

$$FG_{jnt} \;=\; FG_{jn(t-1)} + \sum_{m\in M}\sum_{u\in U_{mn}} Q_{jumn(t-LT_{umn})}$$

$$-\sum_{c\in C}\sum_{u\in U_{nc}} Q_{junct} \qquad \forall j,n,t \qquad (5.12)$$

$Note: Q_{jumnt} = 0, for\ all\ (t - LT_{umn}) \le 0$

3.3. Ending inventory constraint (for initializing the inventory for the next planning cycle)

$$FG_{jnt} \;=\; EndFG_{jn} \qquad \forall j,n,t = T \qquad (5.13)$$

4. At the customer zones

4.1. Customer demand fulfillment constraints: To ensure that the quantity of finished product j shipped to customer c in period t meets the minimum customer demand fulfillment requirement, but it cannot exceed the forecasted demand. Variable W_{jct} represents the unfulfilled demand of product j to customer c in period t. f_{jct} is the fraction of product j to customer c that a company desires to satisfy in period t.

$$f_{jct}D_{jct} \leq d_{jct} \leq D_{jct} \qquad \forall j,c,t \tag{5.14}$$

$$W_{jct} = D_{jct} - d_{jct} \qquad \forall j,c,t$$

4.2. <u>Finished product inventory flow balancing constraint:</u> The inventory of finished product j at the end of period t is determined by the inventory carried over from the previous period plus the amount received from plants and DCs less the amount used.

$$FG_{jct} = FG_{jc(t-1)} + \sum_{m\in M}\sum_{u\in U_{mc}} Q_{jumc(t-LT_{umc})} + \sum_{n\in N}\sum_{u\in U_{nc}} Q_{junc(t-LT_{unc})}$$

$$- d_{jct} \quad \forall j,c,t \quad (5.15)$$

$$Note: Q_{jumct} = 0, if\ (t - LT_{umc}) \leq 0, \qquad Q_{junct} = 0, if\ (t - LT_{unc}) \leq 0$$

4.3. <u>Ending inventory constraint</u> (for initializing the inventory for the next planning cycle)

$$FG_{jct} = EndFG_{jc} \qquad \forall j,c,t = T \tag{5.16}$$

4.4. <u>Storage capacity constraint</u>: To ensure that the quantities of finished products inventory are limited by the available space ($SPACE_{ct}$):

$$\left(\sum_{j\in J} S_j FG_{jct}\right) \leq SPACE_{ct} \qquad \forall c,t \tag{5.17}$$

5. **Transportation links capacity and minimum shipping requirement constraint:** (5.18)

$$MIN_{ukmt}X_{ukmt} \leq \sum_{i\in I} Q_{ikmut} \leq CAP_{ukmt}X_{ukmt} \qquad \forall k,m,u,t$$

$$MIN_{umnt}X_{umnt} \leq \sum_{j\in J} Q_{jumnt} \leq CAP_{umnt}X_{umnt} \qquad \forall m,n,u,t$$

$$MIN_{unct}X_{unct} \leq \sum_{j \in J} Q_{junct} \leq CAP_{unct}X_{unct} \qquad \forall\, n, c, u, t$$

$$MIN_{umct}X_{umct} \leq \sum_{j \in J} Q_{jumct} \leq CAP_{umct}X_{umct} \qquad \forall\, m, c, u, t$$

6. Non-negativity constraints: (5.19)

$$Q_{pufdt} \geq 0 \qquad \forall\, p, f, d, u \in U_{fd}, t$$

$$RM_{imt} \geq 0 \qquad \forall i, m, t$$

$$FG_{jft} \geq 0 \qquad \forall j, f, t$$

$$d_{jct} \geq 0 \qquad \forall j, c, t$$

$$W_{jct} \geq 0 \qquad \forall j, c, t$$

Note: There are no binary variables in the tactical model.

Demand Fulfillment

From the demand fulfillment value in each period (d_{jct}), we can determine the overall customer responsiveness at each customer zone over a planning horizon (d_c). It is the summation of the demand fulfillment of all finished product (d_{jct}) over time taken from the constraint (5.14) divided by total forecasted demand at each customer zone.

$$d_c = \left(\sum_{t \in T} \sum_{j \in J} d_{jct} \Big/ \sum_{t \in T} \sum_{j \in J} D_{jct} \right) \times 100$$

In addition, an overall demand fulfillment (d_{all}) for the supply chain can be determined as follow:

$$d_{all} = \left(\sum_{t \in T} \sum_{c \in C} \sum_{j \in J} d_{jct} \Big/ \sum_{t \in T} \sum_{c \in C} \sum_{j \in J} D_{jct} \right) \times 100$$

Under the disruption-free scenario, the demand fulfillment calculation explained above may not differ from the one from the strategic model. However, it is possible that the minimum demand fulfillment (f_{jct}) may be unachievable for all customer zones when a supply chain experience a disruption. To avoid infeasible solution due to the minimum demand fulfillment requirement in constraint (5.14), we will modify the minimum demand fulfillment constraint as a goal constraint, which will be discussed in Chapter 6.

5.3 Illustrative example for the tactical model

We use the same supply chain example described in Chapter 4. We assume that from the strategic decision, the company selects the supply chain network design solution that consists of suppliers K1 and K3, plants M1 and M2, distribution center (DC) N2, and transportation link type U1 to ship items between facilities, as shown in Figure 5.3. Finished products are shipped to customers via DC N2. There is no direct shipment from plants to customers. In addition, the strategic model recommend no purchasing between supplier K1 and plant M1 to reduce cost.

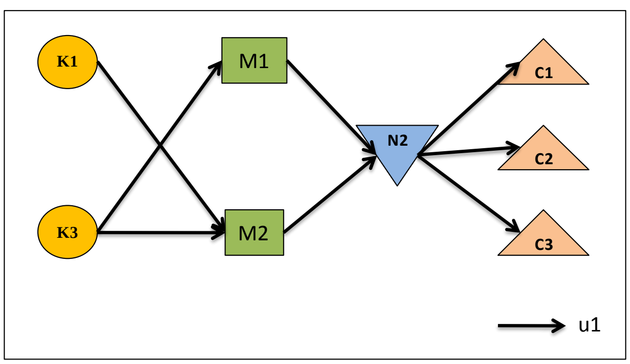


Figure 5.3: Supply Chain Network from the strategic model

The company now wants to develop a tactical plan for a 12-periods planning horizon. We use the following data to illustrate the supply chain network tactical model. These parameters are constants over the planning horizon. Note that the forecasted demand for each customer and product is the average demand from the strategic data. For the lost sales cost, we set a customer goodwill cost at 20% of the estimated profit margin. The estimated profit margin is the selling price minus the estimated unit cost of product. Customer zone C2 is the most profitable customer; hence, the lost sales cost is the highest, followed by customer zones C1 and C3.

Table 5.3: Customers and forecasted demand data

	Customer zone C1		Customer zone C2		Customer zone C3	
SPACE(c,t)	100000		100000		100000	
HC(c,t)	5		7		5	
	j1	j2	j1	j2	j1	j2
D(j,c,t)	4500	4500	4500	3000	2100	2500
f(j,c,t)	0.9	0.9	0.9	0.9	0.9	0.9
SP(j,m,c,t)	450	450	550	550	450	450
SP(j,n,c,t)	500	500	600	600	500	500
LC(j,c,t)	440	440	560	560	400	400

Table 5.4: Suppliers and raw materials data

	Supplier K1		Supplier K3	
	i1	i2	i1	i2
CAP(i,k,t)	20000	20000	45000	45000
MIN(i,k,t)	1000	1000	1000	1000
MC(i,k,t)	10	8	12	10

Table 5.5: Plants and production data

	Plant M1		Plant M2	
SPACE(m,t)	250000		250000	
HC(m,t)	2		3	
	j1	j2	j1	j2
CAP(j,m,t)	20000	20000	20000	20000
MIN(j,m,t)	1000	1000	1000	1000
PC(j,c,t)	15	20	16	21

Table 5.6: Distribution center data

	DC N2	
SPACE(n,t)	250000	
HC(n,t)	4	
	j1	j2
S(j)	8	8
SC(j,n)	2.5	2.5

Table 5.7: Transportation link between suppliers and plants data

i	u	k	m	TC(i,u,k,m,t)
i1	U1	K1	M1	3
			M2	3
		K3	M1	2.1
			M2	2.1
i2	U1	K1	M1	3.6
			M2	3.6
		K3	M1	2.7
			M2	2.7

u	k	m	CAP(u,k,m,t)	MIN(u,k,m,t)	LT(u,k,m)
U1	k1	M1	40000	500	1
		M2	40000	500	
	k3	M1	40000	500	1
		M2	40000	500	

Table 5.8: Transportation link between plants and DC data

j	u	m	n	TC(j,u,m,n,t)
j1	U1	M1	N2	10
		M2	N2	12
j2		M1	N2	10
		M2	N2	12

u	m	n	CAP(u,m,n,t)	MIN(u,m,n,t)	LT(u,m,n)
U1	M1	N2	40000	500	1
	M2	N2	40000	500	

Table 5.9: Transportation link between DC and customers data

j	u	n	c	TC(j,u,n,c,t)
j1	U1	N2	C1	7
			C2	7
			C3	7
j2	U1	N2	C1	7
			C2	7
			C3	7

u	n	c	CAP(u,n,c,t)	MIN(u,n,c,t)	LT(u,n,c)
U1	N2	C1	20000	500	1
		C2	20000	500	
		C3	20000	500	

Table 5.10: Transportation link between plants and customers data

j	u	m	c	TC(j,u,m,c,t)
j1	U1	M1	C1	30
			C2	30
			C3	30
		M2	C1	36
			C2	36
			C3	36
j2	U1	M1	C1	30
			C2	30
			C3	30
		M2	C1	36
			C2	36
			C3	36

u	m	c	CAP(u,m,c,t)	MIN(u,m,c,t)	LT(u,m,c)
U1	M1	C1	20000	5000	2
		C2	20000	5000	
		C3	20000	5000	2
	M2	C1	20000	5000	
		C2	20000	5000	2
		C3	20000	5000	

5.4 Model Solution

We summarize the disruption-free optimal tactical decisions, which include the raw material procurement plan, the production plan, and the distribution plan.

5.4.1 Procurement Decision

Raw materials are purchased from both suppliers K1 and K3. Over the planning horizon, the company purchases raw materials from supplier K3 more than from supplier K1, as shown in Figure 5.4. In total, 83.22% of the raw materials are purchased from supplier K3, while 16.78% of the raw materials are purchased from supplier K1. This is because supplier K3 has more capacity and a lower cost than supplier K1. Note that the purchasing quantity in period t=12 is zero because the tactical model is solved for only one planning horizon.

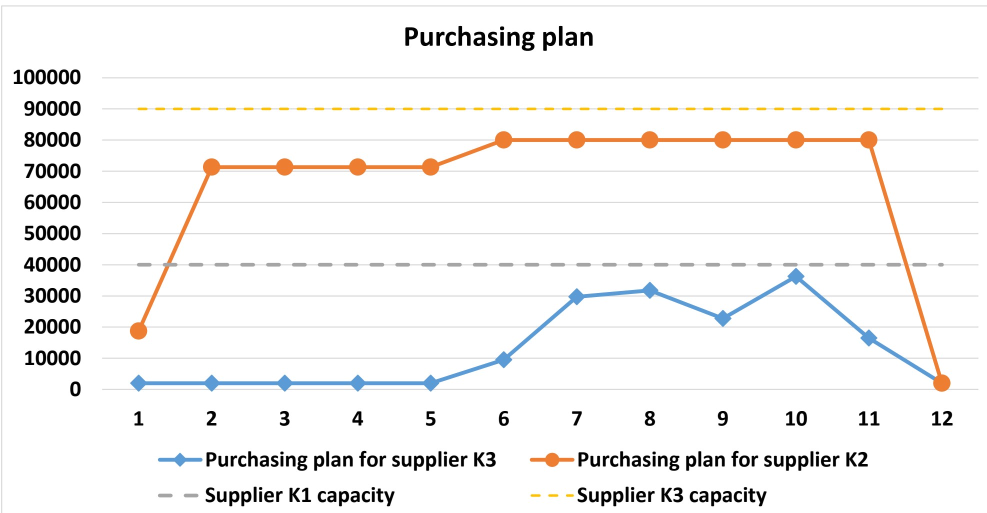


Figure 5.4: Purchasing plan under a disruption-free scenario

5.4.2 Production Decision

Finished products are produced at both plants M1 and M2. Production quantities at both facilities are comparable; plant M1 produces about 48% of the finished products, while plant M2 produces about 52% of the finished products. During periods 1 to 7, the production plan at plant M1 is higher than at plant M2, but after period 7, the production plan at plant M2 is higher than at plant

M1 because plant M2 receives more raw materials provided by supplier K1. The production planning under the disruption-free scenario is shown in Figure 5.5.

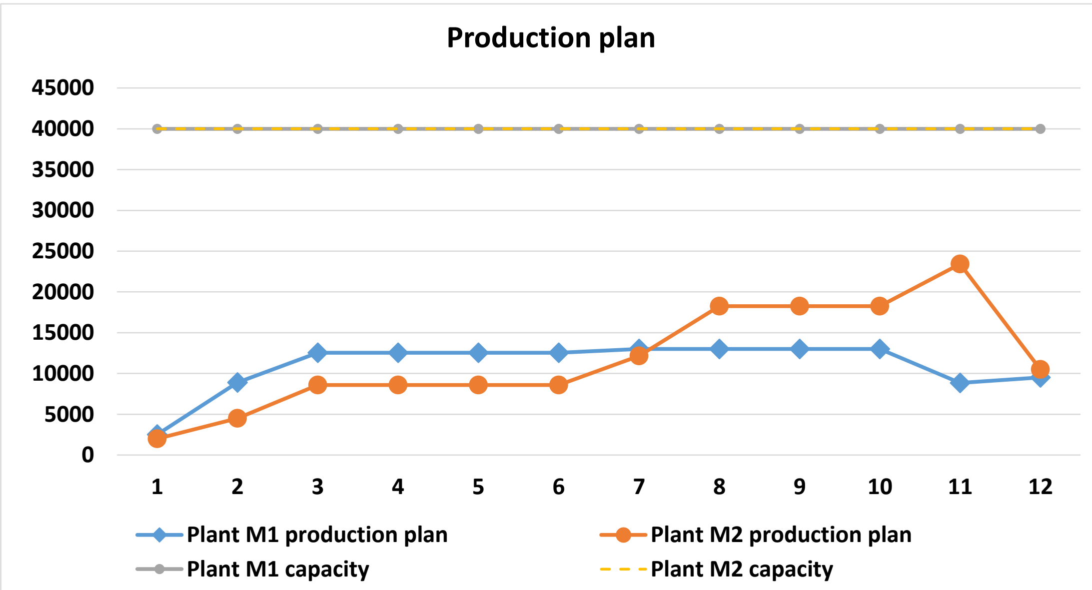


Figure 5.5: Production plan under a disruption-free scenario

5.4.3 Distribution Decision

Under the disruption-free plan, finished products are shipped from DC to all customer zones according to the demand forecasted ($d_{jct} = D_{jct},\ \forall\, j, c, t$). As a result, the overall demand fulfillment at three customer zones are $d_1 = 100\%$, $d_2 = 100\%$, and $d_3 = 100\%$.

5.4.4 Inventory level

Due to the deterministic lead-time and demand, the model suggests not to carry inventory in order to minimize inventory cost. For the modeling purpose, we assign non-zero inventory levels as the initial inventory and the ending inventory. Initial inventory will fulfill customer demand during the first few periods while items are moved from upstream (e.g., suppliers and plants) to customers. Ending inventory will ensure that the initial inventory for the next planning horizon is available. In practice, the tactical model should be run in a rolling horizon. The model will be solved every period for a 12-period planning such that future demand, cost, lead-time, or more updated of the existing data could be taken into account.

5.4.5 Supply chain efficiency (profit) and responsiveness (demand fulfillment)

An optimal supply chain tactical planning decision provides a profit of $114,824,444. The supply chain fulfills all the forecasted demand, in other words, the unfulfilled demand is 0%. Figure 5.6 presents the revenue, cost, and profit profile during the planning horizon. The revenue and supply chain profit at period t=12 are low because the tactical model is solved for only one planning horizon. Figure 5.7 presents a cost breakdown into material cost, production cost, distribution center cost, shipping cost, inventory cost, cross-sourcing cost and lost sale cost. On the average, the material cost is about 35%-40% of the total cost; the shipping cost is about 25-30%; other costs lie between 15%-20%. The lost sale cost is zero because there is no shortage. Note that the inventory cost at the beginning and at the end of the planning horizon are high. This is due to the initial inventory and the ending inventory level constraints. However, an inventory cost during periods t=3 to t=8 is zero because the model suggests not having inventory in order to minimize total cost. Note that the revenue and profit in the last period decrease because the model ends at period t=12.

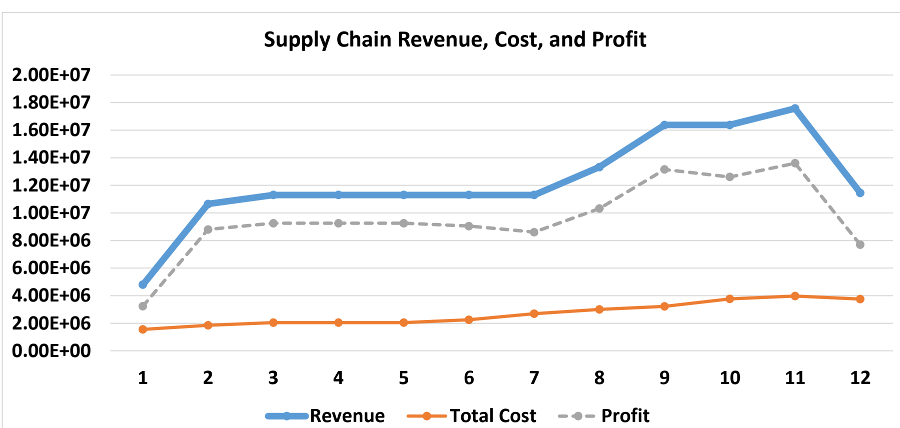


Figure 5.6: Supply chain revenue, cost, and profit profile

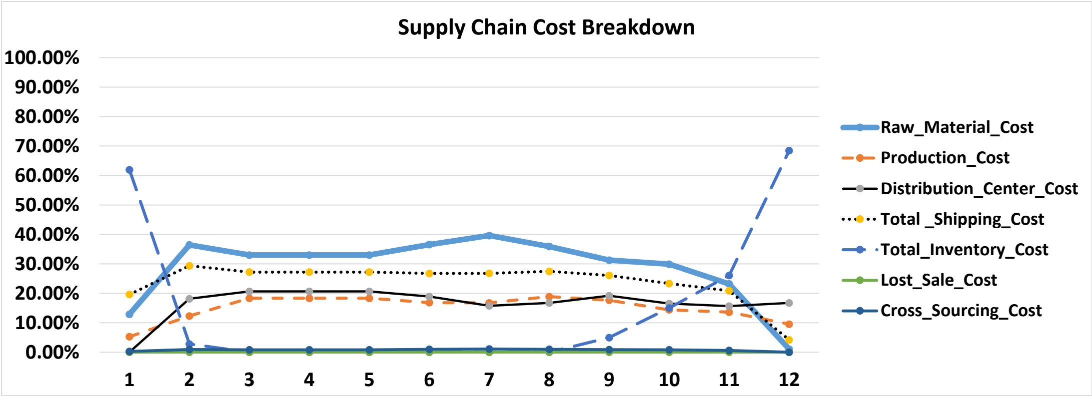


Figure 5.7: Supply chain cost breakdown

5.4.6 Discussion of Results

To maximize the supply chain profit, the disruption-free tactical plan allocates a large amount of raw material purchase to the inexpensive supplier. There is no extra inventory required due to the deterministic lead-time and forecasted demand during the planning horizon. Raw material cost accounts for the largest supply chain cost (about 35-40%), followed by the shipping cost, distribution center cost, and production cost. The disruption-free optimal solution provides 100% demand fulfillment at all customer zones.

5.5 Conclusion

This chapter presents a multi-period deterministic model for supporting a supply chain tactical decision. The model's objective is to maximize the total supply chain profit assuming no disruption or under "normal" operations. Customer demand fulfillment level are specified as model constraints. The optimal decision represents a disruption-free supply chain planning. We will use this decision as a base line to evaluate the vulnerability of the supply chain network operation when facing disruption and to identify the appropriate risk mitigation strategy in the next chapter.

Chapter 6

Vulnerability Analysis and Risk Mitigation Analysis for a Supply Chain Network

6.1 Introduction

The optimal supply chain planning decisions from Chapter 5 represented the maximum profit plan assuming no disruption or under "normal" operations. In fact, disruption may occur at any period during the planning horizon. The disruption-free planning may not perform best when facing a disruption. Therefore, a disruption should be incorporated into supply chain management planning in order to enhance the resiliency of supply chain networks (Klibi and Martel, 2012; Harrison et al., 2013). The supply chain resiliency is an ability of the supply chain to adapt to a disruption and recover from it (Asbjornlett, 1997; 2009), as shown in Figure 6.1.

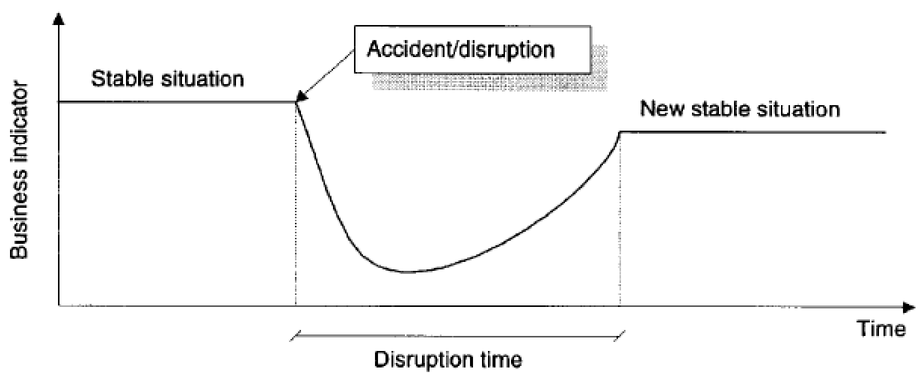


Figure 6.1: Disruption profile of a system from Asbjornlett (1997)

In this chapter, we present a vulnerability analysis and a risk mitigation analysis using a multi-period multi-criteria optimization model. Vulnerability analysis demonstrates the implications of a supply chain component disruption to the supply chain network operation and the supply chain performance, namely supply chain profit and demand fulfillment. Risk mitigation analysis demonstrates the effectiveness of risk mitigation strategies for improving the supply chain resilience and reducing the negative impacts due to disruption. These two analyses are the last two modules in our risk management framework, as shown in Figure 6.2.

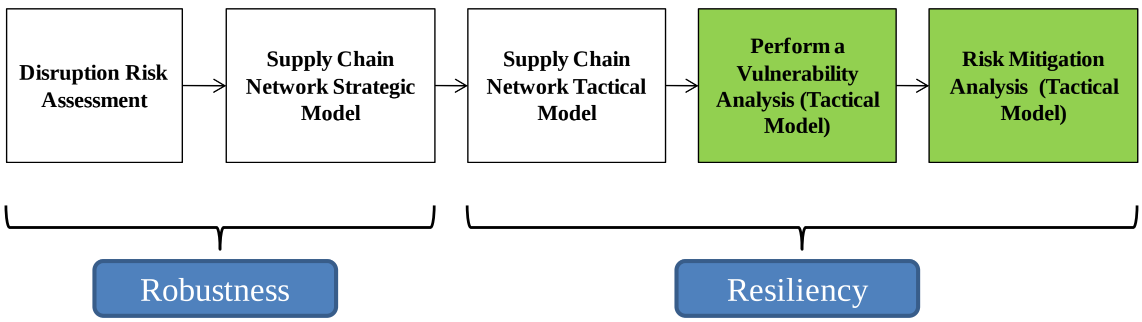


Figure 6.2: Vulnerability Analysis and Mitigation Analysis in a Disruption Risk Management Framework for a Global Supply Chain Network

6.2 Supply Chain Network Vulnerability Analysis

There are a large number of studies related to supply chain vulnerability; however most of them present conceptual frameworks. Mathematical models for quantifying the supply chain vulnerability are still limited. Schmitt and Singh (2009) developed a simulation model to study the implication of disruptions to customer service. The authors applied Monte Carlo analysis to generate a risk profile and used Discrete Event Simulation to model a network flow. The model was also used to evaluate inventory policies. Klibi and Martel (2012) developed a scenario-based risk model to generate future supply chain scenarios using Monte Carlo analysis. In these two studies, multi-period risk profiles were generated to cover a specified planning horizon. Yang (2007) applied analytical models to quantify risk occurrence and risk impact. Bilsel and Ravindran (2012) applied analytical models to quantify detectability time and recovery time. In these two studies, the occurrences and impacts were aggregated for the entire planning horizon. Harrison et al. (2013) proposed an optimization approach, namely Resiliency Enhancement

Analysis via Deletion and Insertion (READI) to improve supply chain network resiliency. READI evaluates the network resiliency when key supply chain node or flow is disabled. It also evaluates the mitigation strategy for resilience improvements. READI was used to illustrate the resiliency improvement at the strategic level for a consumer packaged goods firm in North America, consisting of 5 supply facilities, 4 plants, and 13 DCs.

6.2.1 Supply Chain Network Vulnerability Analysis Framework

In this research, we apply the principle of READI from Harrison et al. (2013) to evaluate the vulnerability and improve the resiliency of the supply chain network. READI approach is summarized below:

Step1: Solve a baseline optimization

Step2: Remove (or insert) a component of the supply chain network

Step3: Re-optimize the supply chain

Step4: Examine the impact of the removal (or insertion) of the supply chain component

We apply the READI approach to the tactical model to evaluate vulnerability of the disruption-free network operation, which is determined from Chapter 5. The disruption-free planning is subjected to a disruption of a supply chain network component (a facility or a transportation link). Each facility and transportation link is prone to different natural or manmade disasters. In addition, occurrence of a disruption, disruption-duration, and disruption impact are also varied depending on the hazard (or risk event), vulnerability of the affected facility or transportation, and availability of risk management practices to cope with a disruption.

The occurrence of some disruptions such as earthquakes is unpredictable, while the occurrence of some disruptions such as floods can be estimated from historical data. The studies from Yang (2007) and Bilsel (2009) quantified occurrences of risk events using Poisson process. Schmitt and Singh (2009) used an exponential distribution to estimate an inter-arrival time of disruptions. Klibi and Martel (2012) modeled hazards arrival process using history data provided by the Federal Emergency Management Agency (FEMA). In our study, we assume that a disruption occurs in the middle of a planning horizon, where supply chain operation is quite stable. It is primarily to illustrate the implications of a disruption to the supply chain operation.

A disruption-duration of a supply chain component represents the time that an affected facility or transportation link cannot perform its function. A disruption-duration can be estimated from publically available historical data, or expert opinion. Bilsel (2009) used exponential random variable to model the recovery time. Schmitt and Singh (2009) used a lognormal distribution to estimate the recovery time. Klibi and Martel (2012) used a discrete random variable to estimate the recovery time in working periods. In our study, a disruption-duration is classified into three cases: short-term (1 period), medium-term (2 periods), and long-term (3 periods), respectively.

The impact of disruption can be measured in different ways, such as customer service (Schmitt and Singh, 2009), financial loss (Yang, 2007; Bilsel, 2009), network capacity and demand (Klibi and Martel, 2012). We measure the disruption impact by comparing the supply chain profit and the demand fulfillment between the disruptive scenario and the disruption-free scenario. We also observe the time it takes for the supply chain network to bounce back to its normal operation to measure the resiliency of the supply chain network.

6.2.2 Modification to the tactical model to support vulnerability analysis

We use the multi-period supply chain tactical model developed in Chapter 5 to perform the vulnerability analysis of the supply chain network operation subject to a supply chain component disruption. Prior to a disruption, we fix the raw materials purchasing quantity, production quantity, and shipping quantity according to the disruption-free decision. To represent a facility or a transportation link disruption, we remove each facility and transportation link by resetting binary parameter corresponding to the affected component from 1 to 0. Then, we re-optimize the model to measure the supply chain profit and demand fulfillment. The new optimal solution indicates how the supply chain should be run when facing disruptions. Harrison et al. (2013) emphasize that re-optimization is essential to determine the impact of disruption.

When a supply chain experiences a disruption, the minimum demand fulfillment constraint specified in the tactical model in Chapter 5 may cause infeasibility due to product shortages. A goal programming (GP) formulation is used to overcome this issue. The minimum demand fulfillment constraint (Eq. 5.14) in the tactical model is re-written as a goal constraint as follows:

The minimum demand fulfillment of product j at customer zone c in period t:

$$d_{jct} \geq f_{jct} D_{jct}$$

This is equivalent to:

$$d_{jct} + d_{jct}^{-} - d_{jct}^{+} = f_{jct} D_{jct}$$

where d_{jct}^{-}, d_{jct}^{+} represent a negative deviation and a positive deviation of the minimum demand fulfillment, accordingly. Therefore, the total negative deviation of minimum demand fulfillment at customer zone c is determined as follows:

$$d_c^- = \sum_{t \in T} \sum_{j \in J} d_{jct}^-$$

If the customer responsiveness levels among the various customer zones are different, a company can assign different weight values (WC_c), using the profit margin or lost sale cost corresponding to each customer zone, to each variable d_c^-. The higher weight value assigns more importance to that customer zone.

To maintain efficiency and customer responsiveness of a supply chain operation under a supply chain component disruption, the tactical model objectives are:

(i) Minimize the underachievement of the supply chain profit (or maximize profit), and

(ii) Minimize the underachievement of the minimum demand fulfillment

We formulate a preemptive GP (P-GP) model and a non-preemptive GP (NP-GP) model as follows:

- Preemptive GP (P-GP) (P_1 and P_2 are priorities for profit and minimum demand fulfillment goals)

$$Min\ z = P_1 d_{profit}^- + P_2 \left(\sum_{c \in C} d_c^- \right) \tag{6.1}$$

Subject to

$$Profit + d_{profit}^- - d_{profit}^+ = Profit\ target$$

$$d_c + d_c^- - d_c^+ = Minimum\ demand\ fulfillment\ target \quad \forall\ c \in C$$

$$d_c^+, d_c^- \geq 0 \quad \forall\ c \in C$$

including the tactical model constraints in Chapter 5.

- Non-preemptive GP (NP-GP) (W_1 and W_2 are numerical weights for profit and minimum demand fulfillment goals)

$$Min\ z = \ W_1 d_{profit}^{-} + W_2 \left(\sum_{c \in C} d_c^{-} \right) \tag{6.2}$$

Subject to

$$\left(\frac{Profit}{Profit\ target}\right) + d_{profit}^{-} - d_{profit}^{+} = 1$$

$$\left(\frac{d_c}{Minimum\ demand\ fulfillment\ target}\right) + d_c^{-} - d_c^{+} = 1 \quad \forall\ c \in C$$

$$d_c^{+}, d_c^{-} \geq 0 \qquad \forall\ c \in C$$

including the tactical model constraints in Chapter 5.

To specify the profit target, we can refer to the disruption-free profit value. For the minimum demand fulfillment target, we can determine the minimum demand fulfillment at each customer zone as $\sum_{t \in T} \sum_{j \in J} f_{jct} D_{jct}$.

In order to maximize the supply chain profit, the model will fulfill the demand of the most profitable customer zone as much as possible, followed by the lesser profitable customer zones. This would result in a lower demand fulfillment for the least profitable customer zone, which may impact future market share. A decision maker may improve the customer responsiveness by increasing the weight of the minimum demand fulfillment goal. However, the improvement at one customer zone will be at the expense of other customers, which also affects the supply chain profit. A company can assign numerical weights corresponding to the preference between these two goals. The higher weight value indicates the more importance. Later, we will show the tradeoff between the profit goal and the minimum demand fulfillment goal with different weight values.

6.3 Illustrative example of vulnerability analysis

We use the NP-GP formulation to perform a vulnerability analysis for the supply chain network obtained from Chapter 5. The supply chain network consists of 2 suppliers (K1 and K3), 2 plants (M1 and M2), 1 DC (N2), and 3 customer zones (C1, C2, and C3). There is one transportation link (U1) connecting between a pair of facilities. From the disruption-free planning, the supply chain profit and the demand fulfillments at all customer zones are $114,824,444 and 100%, respectively. In addition, the minimum demand fulfillment at each customer zones is 90%.

Additional assumptions for the vulnerability analysis are described below:

- Supplier K1 is prone to earthquakes and supplier K3 is prone to floods. Both natural disasters may lead to damages in facilities and transportation links, affecting all supplier operations and outbound transportations. The affected supplier resumes normal function with a full capacity after recovery. For example, if a supplier is disrupted for one period, the parameters X_{ikt} and X_{ukmt} corresponding to the affected supplier are set to zero. After the affected supplier recovers, those parameters are set to one.
- Plants M1 and M2 are prone to floods affecting production and outbound transportations from the affected plant to DCs or customers. These floods, however, do not affect in-transit items and inventory because they can be relocated to secured locations. An affected plant resumes its normal operation with a full capacity after recovery. For example, if a plant is disrupted for one period, the parameters X_{jmt} and X_{umnt} corresponding to the affected plant are set to zero. After the affected plant M1 recovers, those parameters are set to one.
- DC N2 is prone to storms, which do not damage the facility but interrupt outbound transportation from the affected DC to customers. In addition, storms do not affect in-transit

items and inventory at DC because they can be relocated to secured locations. The DC resumes its normal operation after recovery. For example, if a DC is disrupted for one period, the parameter X_{unct} corresponding to the affected DC is set to zero. When the affected DC resumes operations, the parameter X_{unct} is set to one.

- Disruption at a transportation link interrupts only the shipment between a specific pair of facilities. For example, a disruption at link N2-C1 implies that products cannot be shipped from DC N2 to customer zone C1. The parameter X_{ufdt} corresponding to facilities f and d is set to zero.
- Costs due to damages in the facilities and transportation links are not included in the supply chain profit function. In addition, forecasted customer demands are not affected by a disruption.

6.3.1 Analysis of Disruptions

We generate 13 disruptive scenarios; each represents a disruption at a facility or a transportation link.

- There are 2 scenarios created for supplier disruptions (suppliers K1 and K3)
- There are 2 scenarios for plant disruptions (plants M1 and M2)
- There is one scenario of a disruption at the distribution center (DC) N2
- There are 8 scenarios created for transportation link disruptions, including 3 transportation links between the suppliers and the plants (K1-M2, K3-M1, K3-M2), 2 transportation links between the plants and the DC (M1-N2 and M2-N2), and 3 transportation links between the DC and the customer zones (N2-C1, N2-C2, and N2-C3)

For each disruptive scenario, we also consider three disruption-durations: short-term, medium-term, and long-term. In total, we solve 13x3 = 39 optimization models for the vulnerability analysis.

For illustration, we assume that a disruption occurs in the middle of a planning horizon, and the disruption-durations are 1 period, 2 periods, and 3 periods. For example, if a disruption occurs at period t=5, then the disrupted facility (or transportation link) could resume its normal operation at periods 6, 7, or 8, respectively. We summarize the re-optimization process to the tactical model as follows:

Step1: Set the raw material purchasing quantity, production quantity, distribution quantity, and inventory prior to the disruption period (e.g., t = 1, 2, 3, and 4) according to the disruption-free planning.

Step2: Reassign the binary parameter corresponding to the disrupted facility (or transportation link) at the disruption period from 1 to 0. For example, if supplier K1 is disrupted for short-term, then assign $X_{ikt}(1,1,5)$, $X_{ikt}(2,1,5)$, $X_{ukmt}(1,1,1,5)$, and $X_{ukmt}(1,1,2,5)$ to zero. If supplier K1 is disrupted for long-term, then assign those parameters for t=5, 6, and 7 to zero.

Step3: Re-optimize the tactical model and compare the new supply chain network profit and the demand fulfillment with those for the disruption-free scenario. The difference represents the impact of the disruption.

The optimization software LINGO 13.0 is used to solve the models. Throughout this section, we solve the NP-GP model to maximize the supply chain profit (W_1 = 1.0, W_2 = 0.0). The impacts of short-term supply chain disruptions are presented in Table 6.1, in terms of the total unfulfilled demand, the supply chain profit, and the profit reduction due to the disruption.

Table 6.1: Impact of a disruption from a short-term disruption

Supply chain component	Scenario	Disrupted component	Disruption in period t=5 Unfulfilled Demand	Profit ($)	Profit Reduction due to Disruption ($)
Suppliers	1	K1	0.00%	$ 114,822,000	$ 2,444
	2	K3	4.38%	$ 105,683,067	$ 9,141,377
Plants	3	M1	4.95%	$ 104,332,229	$ 10,492,215
	4	M2	3.39%	$ 107,661,033	$ 7,163,411
DC	5	N2	8.33%	$ 94,799,728	$ 20,024,716
Transportation Links	6	K1-M2	0.00%	$ 114,822,000	$ 2,444
	7	K3-M1	0.79%	$ 113,092,871	$ 1,731,573
	8	K3-M2	0.00%	$ 114,731,671	$ 92,773
	9	M1-N2	4.95%	$ 104,328,229	$ 10,496,215
	10	M2-N2	3.39%	$ 107,653,876	$ 7,170,568
	11	N2-C1	3.55%	$ 106,961,917	$ 7,862,527
	12	N2-C2	2.96%	$ 106,625,954	$ 8,198,490
	13	N2-C3	1.82%	$ 111,002,257	$ 3,822,187

From Table 6.1, a short-term disruption at supplier K1 (scenario 1), transportation links K1-M2 (scenario 6), and transportation link K3-M2 (scenario 8) does not affect the customer responsiveness (unfulfilled demand = 0%). However, a short-term disruption at other facilities or transportation links leads to unfulfilled demand. For instance, a disruption at supplier K3 (scenario 2) will lead to 4.38% of unfulfilled demand, and $9.14 million profit reduction from the disruption-free planning. Disruption at DC N2 causes the most impact in terms of unfilled demand (8.33%) and profit reduction ($20 million). Tables 6.2 and 6.3 present the impact of medium-term and long-term disruptions. The results show that the supply chain cannot fulfill customer demands as planned when disruptions occur. In addition, DC N2, supplier K3, and plant M2 are the top three facility disruptions causing the highest unfulfilled demand and profit reduction under medium and long-term disruptions.

Table 6.2: Impact of a disruption from a medium-term disruption

Supply chain component	Scenario	Disrupted component	Disruption in periods t = 5, 6 Unfulfilled Demand	Profit ($)	Profit Reduction due to Disruption ($)
Suppliers	1	K1	0.49%	$ 114,000,580	$ 823,864
	2	K3	10.59%	$ 93,193,650	$ 21,630,794
Plants	3	M1	4.95%	$ 104,095,448	$ 10,728,996
	4	M2	6.58%	$ 100,791,372	$ 14,033,072
DC	5	N2	16.67%	$ 74,752,426	$ 40,072,018
Transportation Links	6	K1-M2	0.49%	$ 114,000,580	$ 823,864
	7	K3-M1	1.81%	$ 110,808,159	$ 4,016,285
	8	K3-M2	0.07%	$ 114,439,334	$ 385,110
	9	M1-N2	4.95%	$ 104,083,448	$ 10,740,996
	10	M2-N2	6.58%	$ 100,771,847	$ 14,052,597
	11	N2-C1	7.11%	$ 99,209,336	$ 15,615,108
	12	N2-C2	5.92%	$ 98,525,913	$ 16,298,531
	13	N2-C3	3.63%	$ 107,248,873	$ 7,575,571

Table 6.3: Impact of a disruption from a long-term disruption

Supply chain component	Scenario	Disrupted component	Disruption in periods t = 5, 6, 7 Unfulfilled Demand	Profit ($)	Profit Reduction due to Disruption ($)
Suppliers	1	K1	3.95%	$ 107,686,857	$ 7,137,587
	2	K3	19.38%	$ 75,438,020	$ 39,386,424
Plants	3	M1	4.95%	$ 103,818,393	$ 11,006,051
	4	M2	11.27%	$ 91,007,797	$ 23,816,647
DC	5	N2	25.00%	$ 54,841,280	$ 59,983,164
Transportation Links	6	K1-M2	3.95%	$ 107,686,857	$ 7,137,587
	7	K3-M1	2.99%	$ 107,940,351	$ 6,884,093
	8	K3-M2	3.17%	$ 108,661,501	$ 6,162,943
	9	M1-N2	4.95%	$ 103,794,393	$ 11,030,051
	10	M2-N2	11.27%	$ 90,969,511	$ 23,854,933
	11	N2-C1	10.66%	$ 91,550,200	$ 23,274,244
	12	N2-C2	8.89%	$ 90,529,176	$ 24,295,268
	13	N2-C3	5.45%	$ 103,552,099	$ 11,272,345

From Tables 6.1-6.3, we observe the following:

- Disruptions at facilities result in more negative impacts to the supply chain than disruptions at the transportation links.

- Among all the facilities, disruptions at DC N2 cause the most negative impacts to the supply chain due to the centralized distribution center, followed by disruptions at supplier K3 and plant M2.
- Among all the transportation links, disruptions at the links connecting between the plants and DC N2 result in high negative impacts to the supply chain, followed by disruptions at the links connecting between the DC and the customers, and the links connecting between the suppliers and the plants.

6.3.2 Detailed analysis of Scenario 2

Let's examine the customer responsiveness at each customer zone when supplier K3 experiences a short-term disruption in period t=5 (Scenario 2). From Table 6.1, a disruption at supplier K3 in period 5 incurs 4.38% shortages of the total forecasted demands. Figure 6.3 presents the customer demand fulfillment over time when the supply chain profit goal is more important than the minimum demand fulfillment goal (W_1 = 1.0 and W_2 = 0). The demand fulfillments over time at customer zone C2, which has the highest profit margin, are 100%. The demand fulfillment at customer zone C1 in period 8 is 94.7%, which still meets the minimum demand fulfillment requirement. The demand fulfillments at customer C3, which has the lowest profit margin, during periods 6-8 are 47.3%, 10.9%, and 10.9%, which are below the minimum demand fulfillment level. The supply chain profit is $105,683,067.

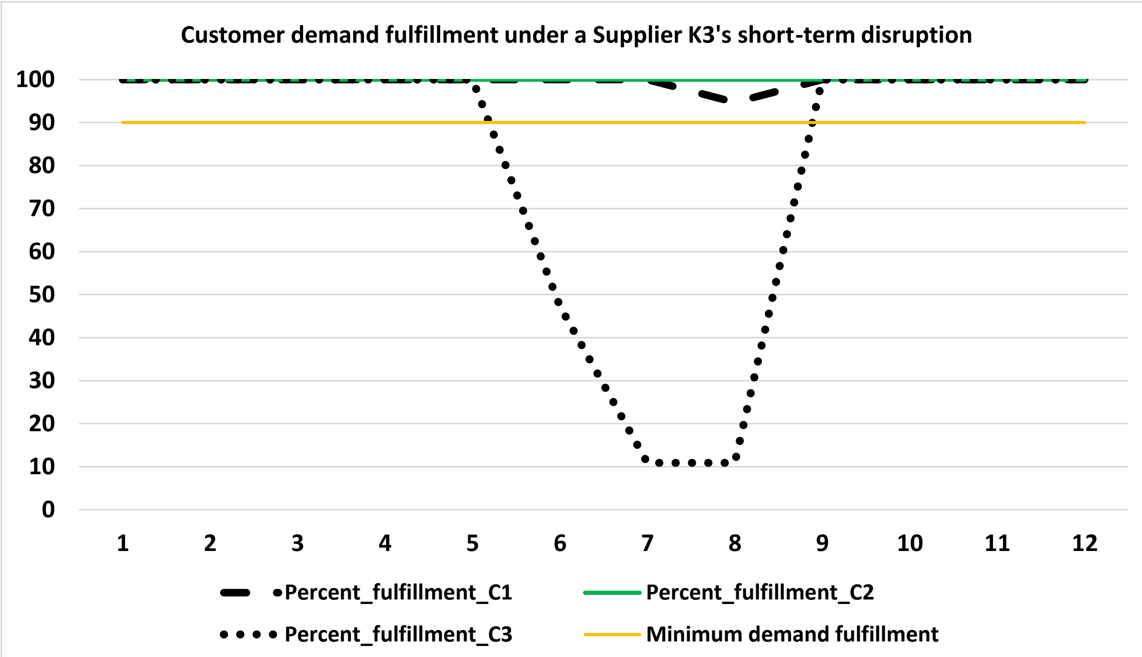


Figure 6.3: Customer demand fulfillment under a short-term disruption at supplier K3 (W_1 = 1.0 and W_2 = 0)

The poor demand fulfillment at customer zone C3 could lead to the loss of customer C3. We can study the tradeoff between supply chain profit and minimum demand fulfillment using different objective weight values. Figure 6.4 presents the demand fulfillment over time at each customer, when the minimum demand fulfillment goal is more important than the profit goal (W_1 = 0.00001, W_2 = 0.99999). We use the lost sales cost to determine the weights of the negative deviation of minimum demand fulfillments (WC_1 = 440/560, WC_2 = 560/560, and WC_3 = 400/560). The results show that the demand fulfillment at customer zone C2 (the most profitable customer) remains unchanged, while the demand fulfillment at customer zone C1 (the second profitable customer) in periods 7 and 8 are decreased to 94.4% and 43.5%. The demand fulfillments at customer C3 (the least profitable customer) during periods 6-8 are increased to 100%, 45.6%, and 34.3%. Therefore, the responsiveness improvement at customer zone C3 has occurred at the expense of customer zone C1 due to the importance of minimum demand fulfillments. The supply chain profit is decreased from $105,683,067 to $105,601,959.

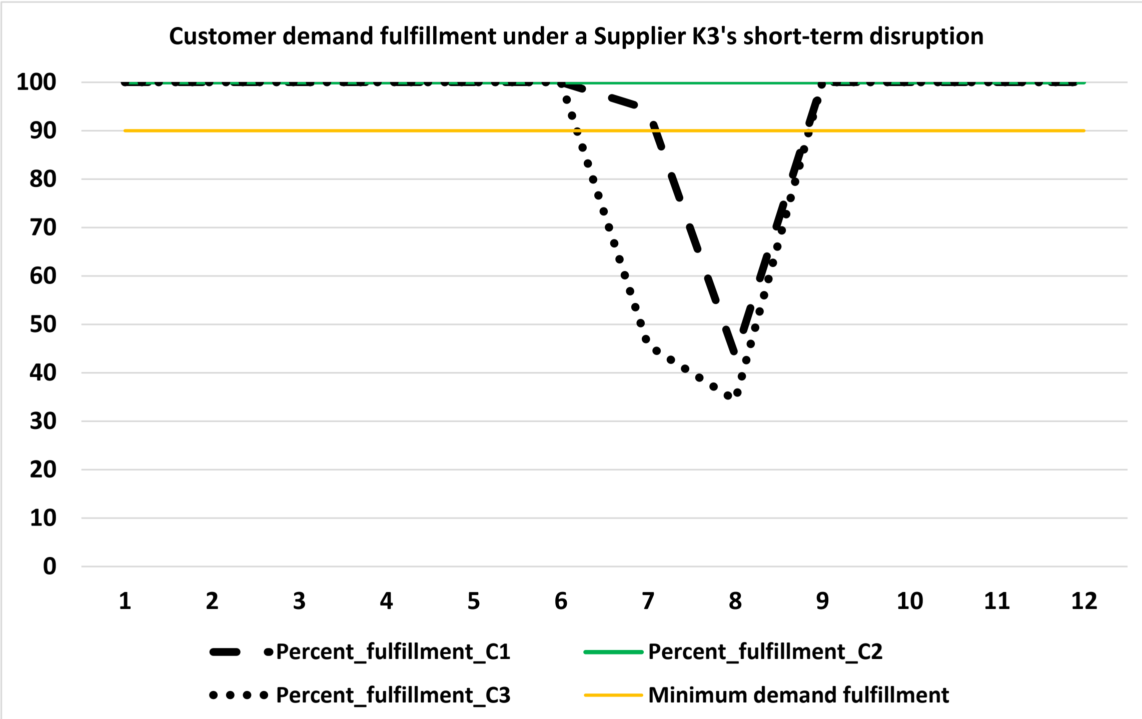


Figure 6.4: Customer demand fulfillment under a short-term disruption at supplier K3 (W_1 = 0.00001 and W_2 = 0.99999)

Figure 6.5 presents the demand fulfillment over time at each customer when the supply chain profit goal and the minimum demand fulfillment goal are equally important ($W_1 = W_2 = 0.5$). The results show that the demand fulfillment at customer zone C2 remains unchanged, while the demand fulfillments at customer zone C1 during periods 7 and 8 are 88% and 50%. The demand fulfillments at customer zone C3 during periods 6-8 are 100%, 45.6%, and 34.4%. The supply chain profit is $105,604,478.

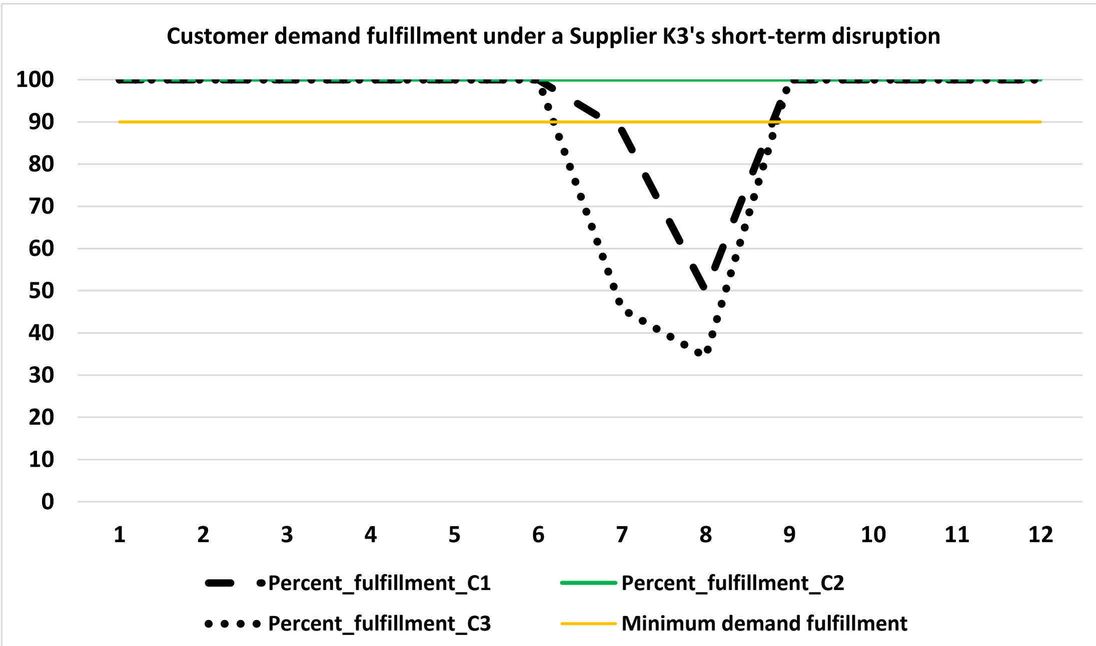


Figure 6.5: Customer demand fulfillment under a short-term disruption at supplier K3 (W_1 = 0.5 and W_2 = 0.5)

Figure 6.6 shows the supply chain profits over time for different objective weights.

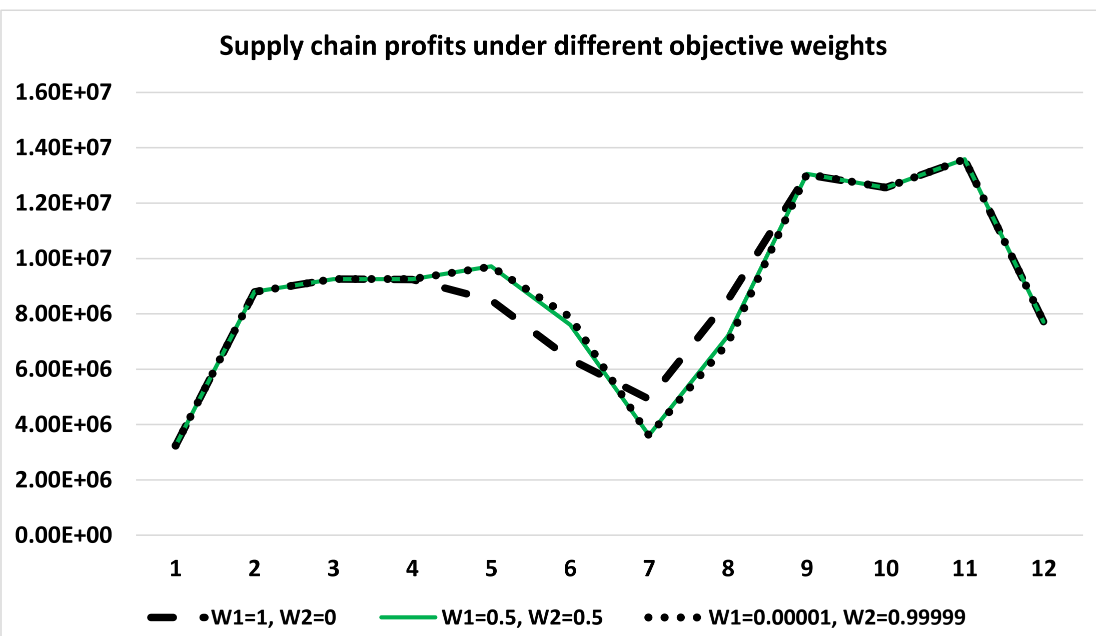


Figure 6.6: Supply chain profits with different objective weights

Figure 6.6 presents the supply chain profit impact with respect to demand fulfillment. Consider the two cases, when the profit goal is more important than the minimum demand fulfillment goal (W1 = 1.0, W2 = 0.0) and when the minimum demand fulfillment goal is more important than the profit goal (W1 = 0.00001, W2 = 0.99999). The improvement in the demand fulfillment at customer zone C3 increases the supply chain profit during periods 5 and 6. However, the reduction in the demand fulfillment at customer zone C1 results in the profit reduction during periods 7 and 8.

6.4 Further Analysis of Disruption Risks

Results of Section 6.3 can be used to develop appropriate risk mitigation strategies, such as backup supplier, alternative transportation route, etc. We shall illustrate this using the various scenarios.

6.4.1 Supplier disruption

Under normal conditions, with no disruption, the supply chain purchases a large amount of raw materials from supplier K3, who is less expensive, to maximize the supply chain profit. Therefore, a disruption at supplier K3 results in more shortages and profit reduction than a disruption at supplier K1 (see scenario 1 and 2 results). Figure 6.7 shows the purchasing plan of the disruption-free scenario, the total purchasing quantity from suppliers K1 and K3 in period t=5 are 2,000 and 71,300 units. When supplier K3 is disrupted, as shown in Figure 6.8, the company can increase the order of raw materials from supplier K1 only, who has insufficient capacity.

Therefore, the supply chain network experiences raw materials shortages when supplier K3 is disrupted.

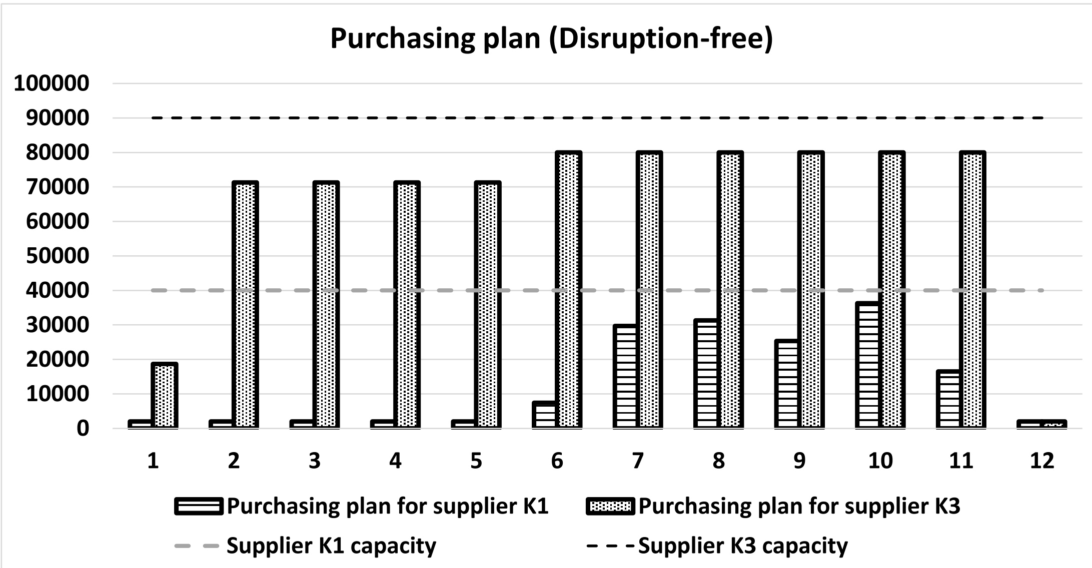


Figure 6.7: Procurement plan under the disruption-free scenario

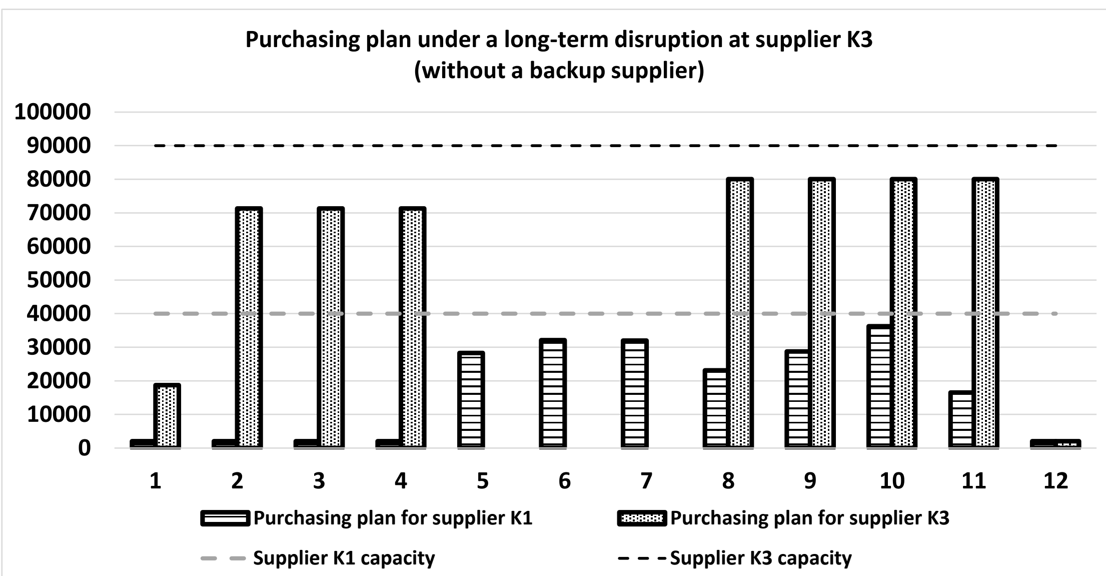


Figure 6.8: Procurement plan under a long-term disruption at supplier K3

Figure 6.9 presents the demand fulfillments over time of all customer zones when supplier K3 is disrupted for a short-term, medium-term, and long-term. The results show that the demand fulfillment cannot return to its normal conditions (the disruption-free scenario) until the affected supplier returns its normal capacity, indicating a lack of supply chain resilience.

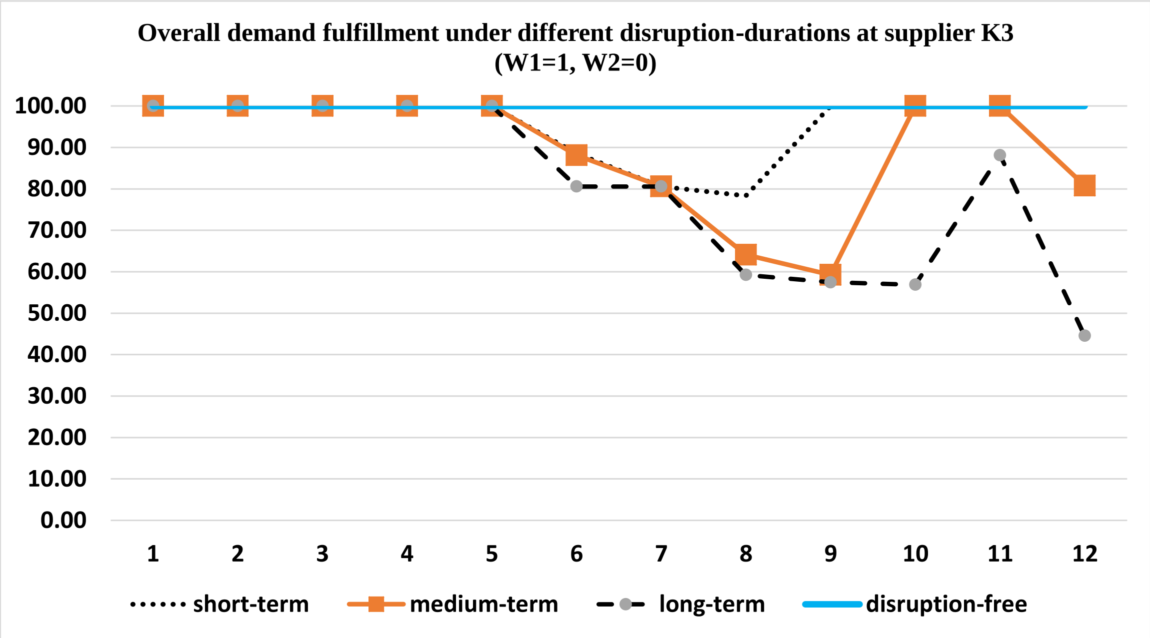


Figure 6.9: Overall demand fulfillment subject to a disruption at supplier K3

Figure 6.10 presents the supply chain profits over time when supplier K3 is disrupted under different disruption-durations. The results show that the supply chain profit takes a longer time to return to its normal value (the disruption-free scenario). For example, a short-term disruption at supplier K3 in period 5 affects the supply chain profit from periods 6 to 8, a medium-term disruption affects profit in periods 6-9, and a long-term disruption impacts profits from periods 6-12. These results imply a lack of resiliency due to inadequate supply capacity. Hence, it is important to develop a risk mitigation plan when supplier K3 is disrupted.

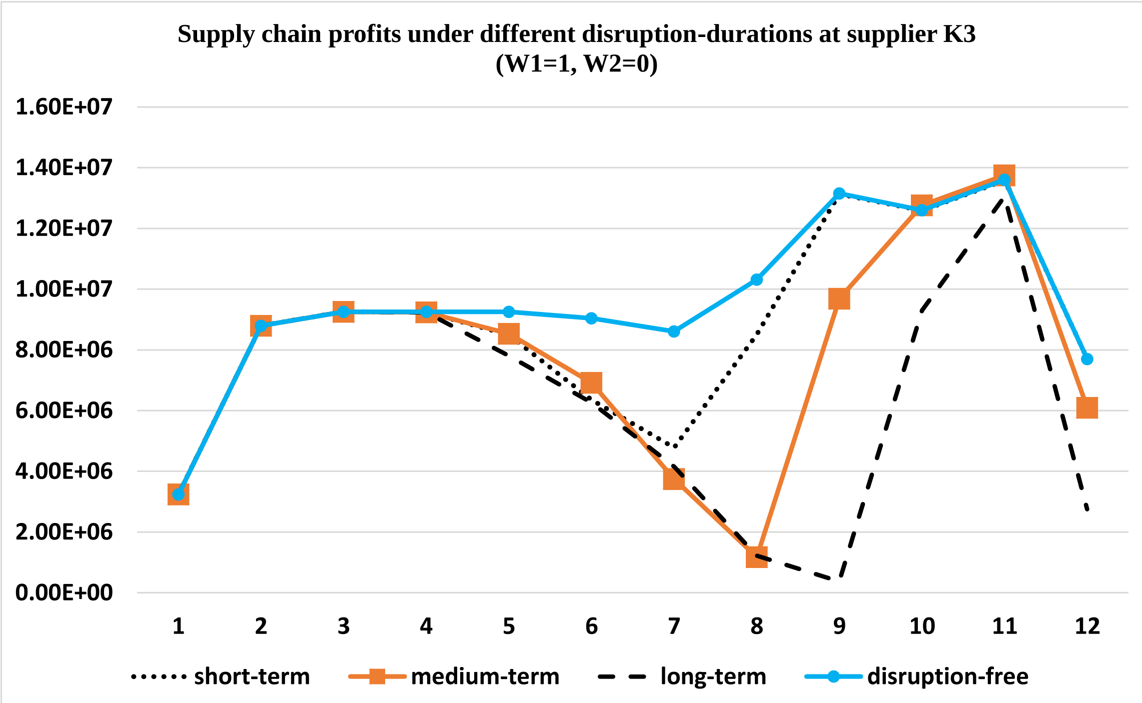


Figure 6.10: Supply chain profits subject to a disruption at supplier K3

Possible risk mitigation strategies to manage a disruption at supplier K3 can be identified using the vulnerability analysis and the disruption risk assessment discussed in Chapter 3. Supplier K3 is prone to floods, which occur during the monsoon season. Floods occur every year. A company may consider increasing supply capacity by carrying extra inventory, having a backup supplier, or re-designing the supply chain network to have more than two suppliers. The cost benefit analysis of these mitigation strategies will be discussed in Section 6.5.

6.4.2 Plant disruption

Under normal conditions, plant M1 receives raw materials only from supplier K3, while plant M2 receives raw materials from both suppliers K1 and K3. When a disruption occurs at plant M1, a company can increase production at plant M2, which has sufficient production capacity. Figures 6.11 and 6.12 present the demand fulfillments and the supply chain profit due to plant M1 disruption under different disruption-durations. The impact on the demand fulfillments and the supply chain profits are the same for all disruption-durations. This indicates that the supply is resilient due to adequate raw materials supply capacity and flexible production facilities. In addition, the company may carry extra finished products inventory at the DC/customer zones or carry extra raw material inventory at plant M2 in order to avoid shortages due to a disruption at plant M1.

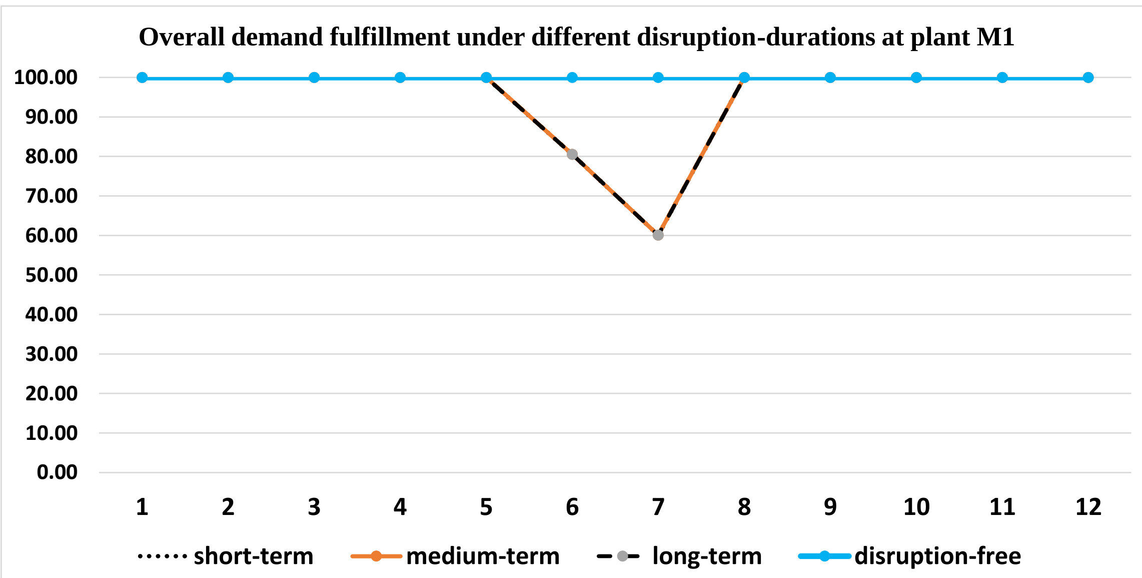


Figure 6.11: Demand fulfillment subject to plant M1 disruptions

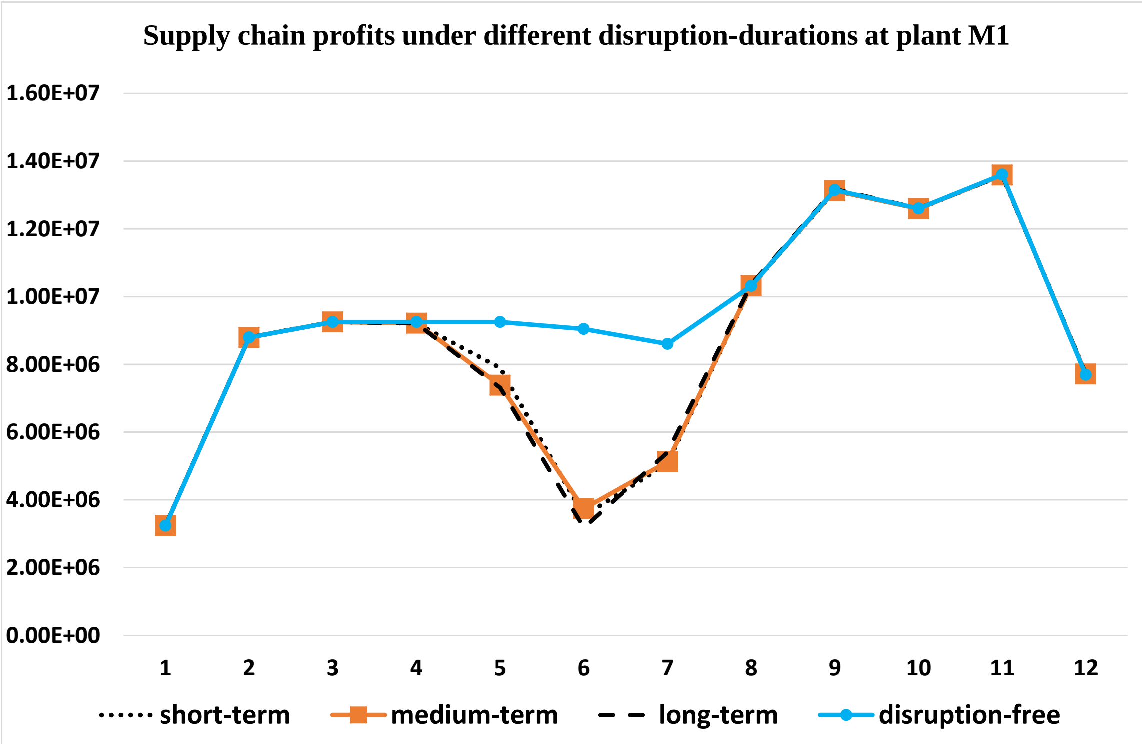


Figure 6.12: Supply chain profits subject to plant M1 disruptions

If a disruption occurs at plant M2, both the demand fulfillment and the supply chain profit are severely affected and cannot return to a stable condition (the disruption-free scenario) until the affected plant is fully operational, as shown in Figures 6.13 and 6.14. These results indicate a lack of supply chain resiliency due to inadequate raw materials. Recall that the strategic model recommends no purchasing between supplier K1 and plant M1 to reduce cost. Even though plant M1 is not operating at capacity, it cannot increase production at M1 because of insufficient raw materials. Therefore, a company may consider a dual-sourcing strategy at plant M1 to ensure adequate supply capacity. The cost benefits of different mitigation strategies for plant disruption will be discussed in Section 6.5.

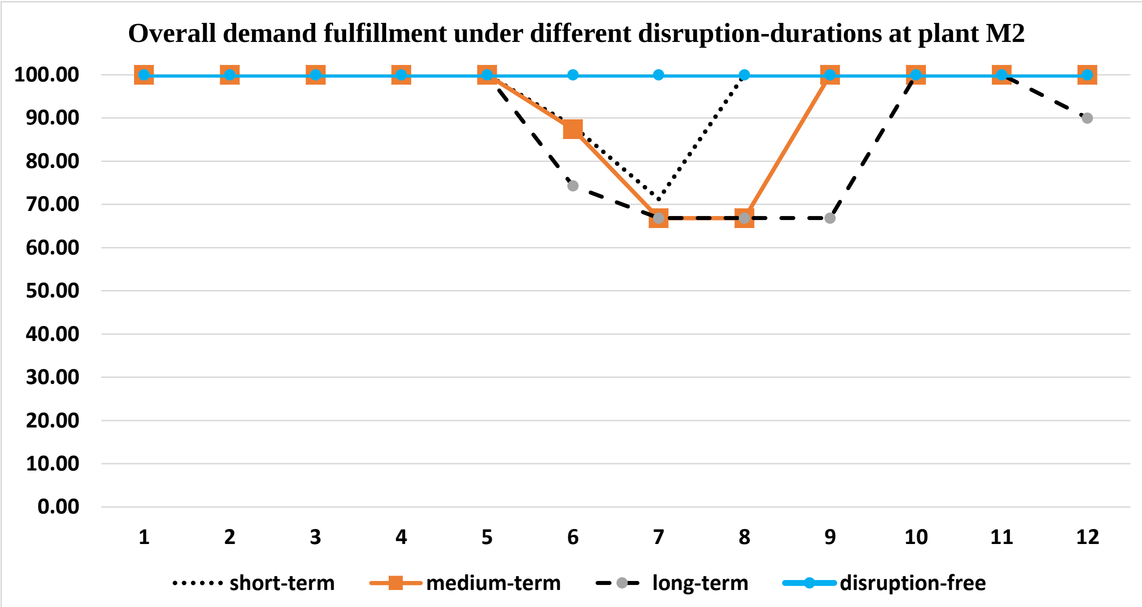


Figure 6.13: Demand fulfillment subject to plant M2 disruptions

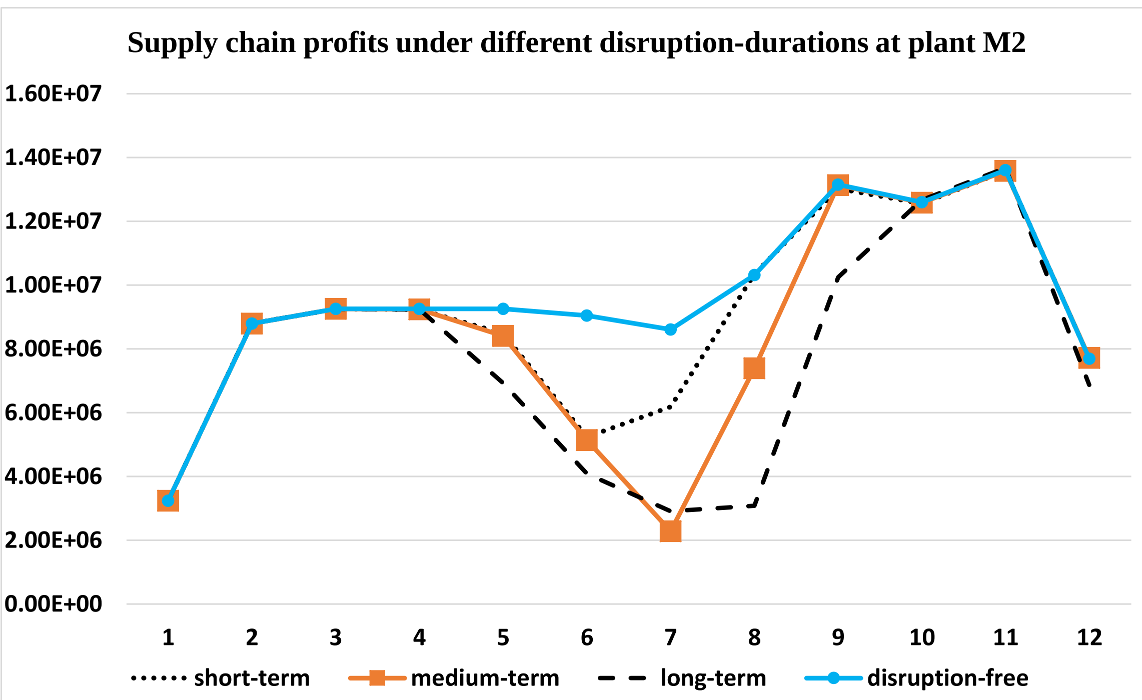


Figure 6.14: Supply chain profits subject to plant M2 disruptions

6.4.3 DC disruption

Under the disruption-free planning, finished products are shipped to customers via DC N2. There is no direct shipment from plants to customers. A disruption at DC N2 demonstrates a lack of supply chain resiliency due to a centralized distribution center. Even though a strategic model in Chapter 4 has selected a low-disruption risk distribution center, disruption risk still exists. The impacts of DC N2 disruption to demand fulfillment and supply chain profit are presented in Figures 6.15 and 6.16.

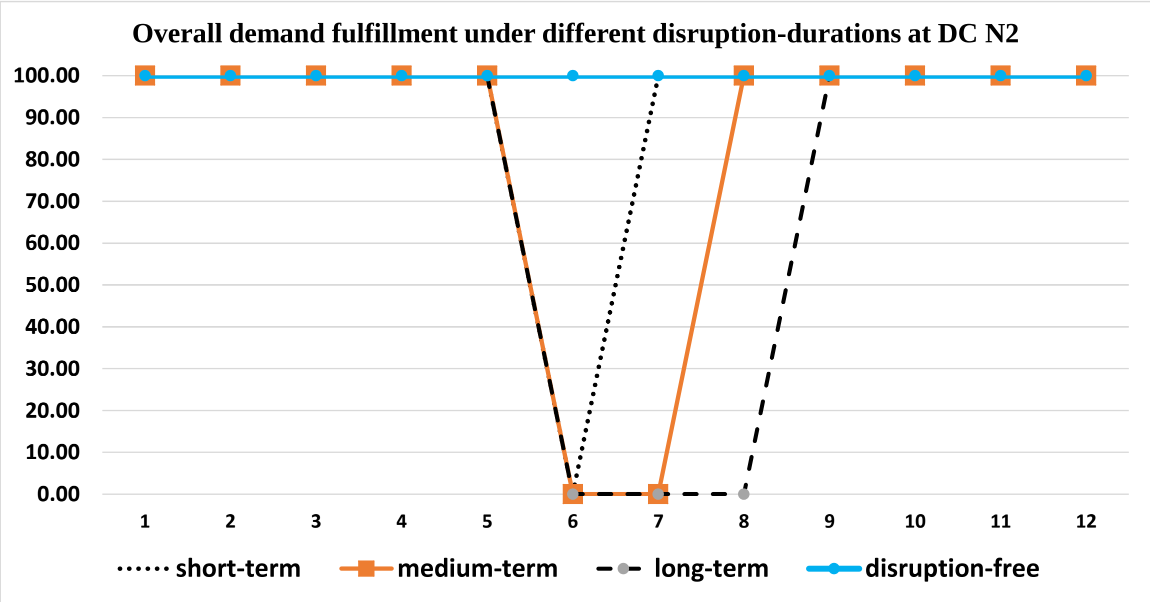


Figure 6.15: Demand fulfillment subject to DC N2 disruptions

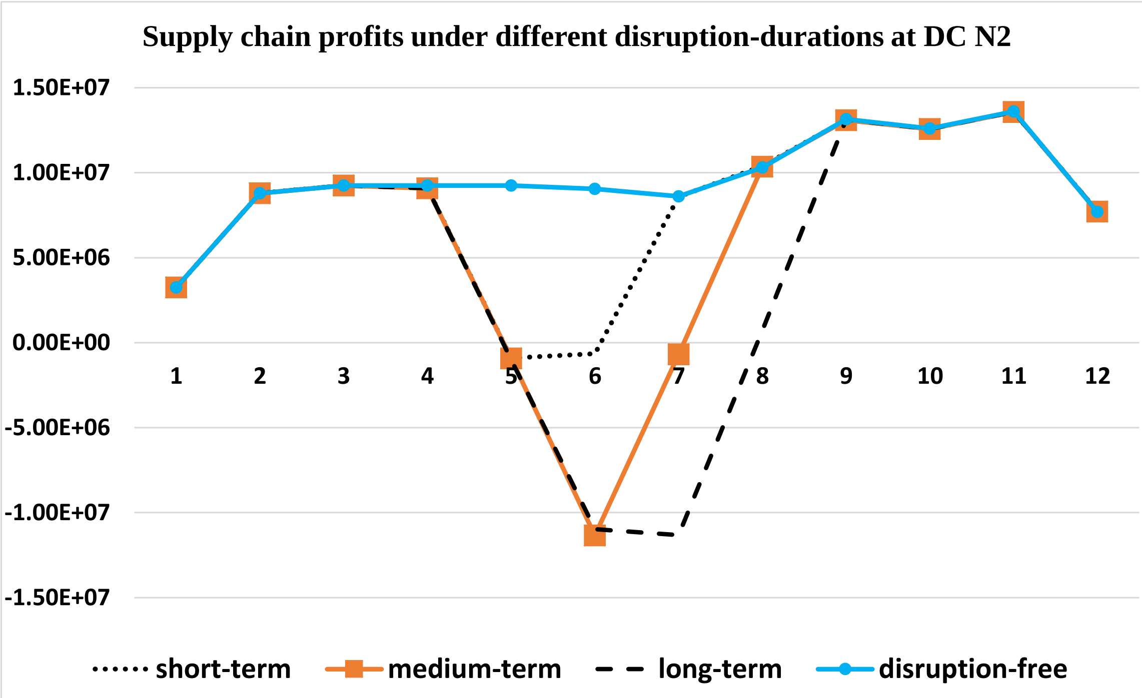


Figure 6.16: Supply chain profit subject to DC N2 disruptions

From the disruption risk assessment in Chapter 3, DC N2 is prone to storms. A company may consider allowing a direct shipment from plants to customer zones, renting a warehouse as a backup facility, or having more than one DC as possible mitigation strategies. The latter strategy is called decentralization or risk diversification strategy to reduce negative impacts due to a disruption (Schmitt, 2008). A supply chain network re-design can be done at the strategic model in Chapter 4 with additional constraint to have more than one distribution center.

6.4.4 Transportation link disruption

From Tables 6.1 – 6.3, we observe a significant impact on unfulfilled demand when a disruption occurs at transportation links between plants to DC and between DC to customers. This is due to the centralized distribution strategy. In addition, a disruption at link N2-C1 (scenario 11) causes the highest unfulfilled demand because of unfilled demand at customer C1, while a disruption at link N2-C2 (scenario 12) causes the highest profit reduction because of the high profit margin at customer C2. From Table 6.2, a medium-term disruption at link N2-C1 causes 7.11% unfulfilled demand and $15.6 million profit reduction, while a medium-term disruption at link N2-C2 causes 5.92% unfulfilled demand and $16.3 million profit reduction. To mitigate possible disruptions at the transportation links, especially from DC to customers, a company may plan for direct shipments from plants to customers, carry extra inventory at customer locations, or have alternate transportation links.

6.5 Risk Mitigation Analysis

Section 6.2 presented the implications of facility and transportation disruptions to the supply chain network operations. We re-optimized the network flow to demonstrate the degree of resiliency of the supply chain network when facing disruptions. In this section, we incorporate risk mitigation strategies, such as a backup facility and extra inventory, to illustrate how the resiliency can be improved for a supply chain network operation.

6.5.1 Risk Mitigation Strategies

To illustrate the risk mitigation analysis, let us consider supplier K3, who has the highest disruption risk score among all supply chain components. We identify two possible risk mitigation strategies: a backup supplier and extra inventory of raw material at the plants. The effectiveness of the risk mitigation strategy is studied by comparing its benefit and cost. In our study, mitigation benefit is the difference between the supply chain profit with the risk mitigation strategy and the supply chain profit without the mitigation strategy. Mitigation cost is the difference between the supply chain operation costs when risk mitigation exists and the supply chain cost under the disruption-free scenario.

For the backup supplier strategy, we assume that the raw materials cost and shipping cost are usually higher than those from a regular supplier. In addition, the availability of a backup supplier may depend on an approval process, effective communication, and risk awareness among entities in a supply chain. If collaboration between a company and a backup supplier has been established beforehand, a backup facility could be added quickly for risk mitigation. On the other hand, if collaboration has not yet been established, it may take several time periods to complete the vendor approval process. A backup supplier strategy can also refer to relocating the inventory. For instance, a few days prior to the Thailand massive floods, Western Digital (Thailand) pulled inventory at suppliers and moved to a safe location. The inventory relocation increased cost but it substantially reduced the total damages and helped to alleviate immediate supply shortages (Wai and Wongsurawat, 2013).

For the extra inventory strategy, inventory can be either raw materials or finished products, and inventory can be located in different locations. This strategy has been used by various companies. For example, IBM holds a higher level of inventory for unreliable suppliers (www.ibm.com). Toyota's North American plants avoided plant shut downs by using inventory that were shipped prior to the Japanese earthquake (http://www.toyotapaloalto.com). Many retailers were able to reduce damages due to supply disruption by building up inventories before the California dockworker's strike (Chopra and Sodhi, 2004).

6.5.2 Risk Mitigation Analysis Results

Case 1: Mitigation strategy: use of backup facility

A backup supplier increases resiliency by providing adequate supply capacity when there is a disruption. Let us analyze the use of a backup supplier when supplier K3 is disrupted. We re-optimize the tactical model under scenario 2 for all three disruption durations. Figure 6.17 shows the raw material purchasing quantity when supplier K3 is facing a long-term disruption. The supply chain orders 40,000 units from supplier K1 and 33,300 units from a backup supplier. The supply chain is able to produce finished products as planned and fulfill all customer demands. The supply chain profit is $114,303,080. In other words, a backup supplier increases profit by about $8.62 million compared to scenario 2 with no risk mitigation, whereas it costs only $0.52 million for the use of backup supplier. Note that these cost and profit are determined based on the assumption that raw materials and shipping costs at a backup supplier are 100% higher than at the affected supplier. Table 6.4 and Figure 6.18 present the supply chain profits when having a backup supplier. There is a significant improvement with a backup supplier, which results in an increase in the supply chain resilience.

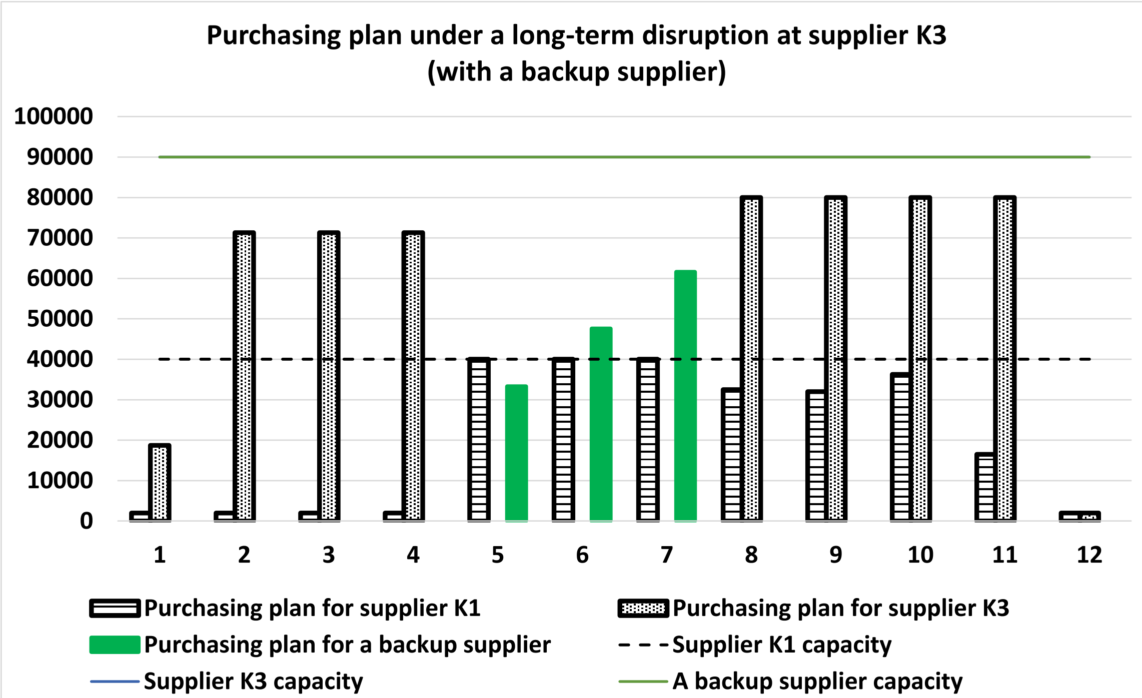


Figure 6.17: Order quantity under a long-term disruption at supplier K3 (with a backup supplier)

Table 6.4: Supply chain profit under case 1 (supplier K3 is disrupted)

Disruption	Normal (Reference)	No backup supplier	With backup supplier
Short-term	$ 114,824,444	$ 105,683,067	$ 114,303,080
Medium-term	$ 114,824,444	$ 93,193,650	$ 113,653,738
Long-term	$ 114,824,444	$ 75,438,020	$ 112,836,241

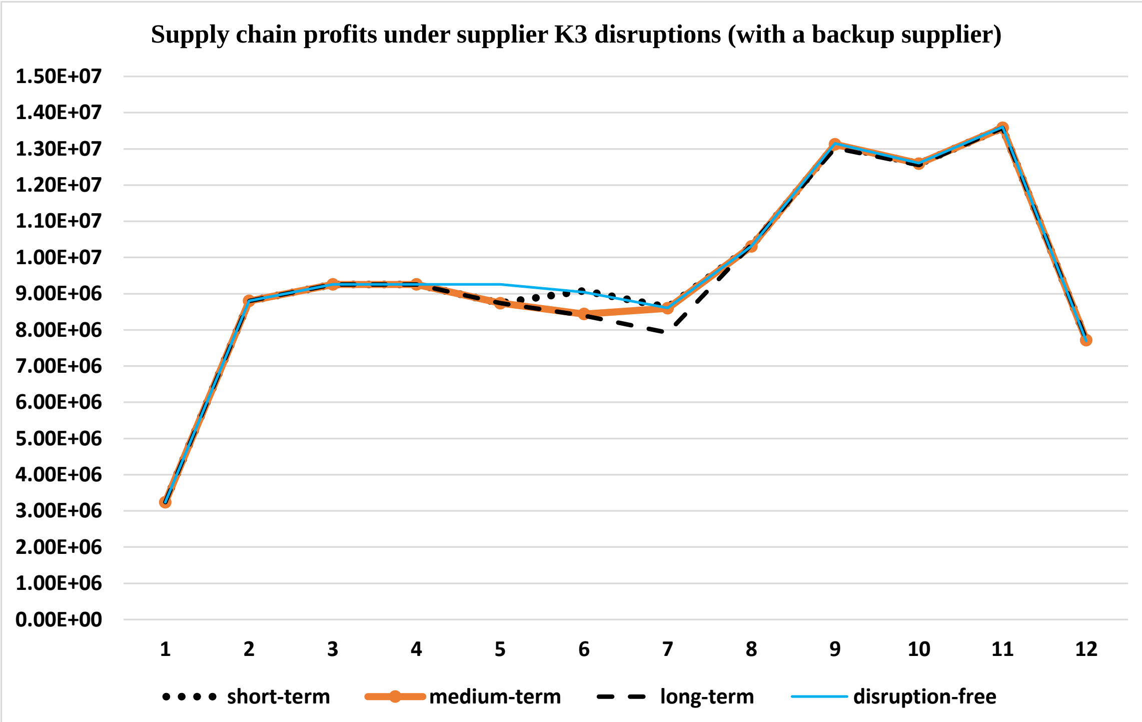


Figure 6.18: The supply chain profits under disruption at supplier K3 (with a backup supplier)

Case 2: Mitigation strategy: carrying extra raw inventory at plant

To incorporate extra inventory in our tactical model, first we solve a supply chain tactical model with the inventory requirement. The optimal solution provides the total profit and supply chain operation cost when risk mitigation exists. Then, we reassign the binary parameters associated with supplier K3 from one to zero to represent a disruption at supplier K3. Note that the determination of inventory location and the amount are not the primary focus in our analysis. We assume that a company can store at most 1-period's lead-time demand at the plant facilities. From the forecast data, the 1-period lead-time demands for finished products j1 and j2 are 11,000 units and 10,000 units, which are equivalent to 31,000 units of raw material i1 and 42,000 units of raw material i2.

Having extra inventory (raw materials, finished products, or both) at plant temporarily prevents shortages when supplier K3 is facing a disruption. In our example, the extra inventory can support the normal production operation at plant M1 when supplier K3 is disrupted for a short-term. Hence, from Table 6.5, the supply chain profit is $114,128,893. In other words, having extra inventory saves about $8.44 million in profit reduction, whereas it costs about $0.68 million. If a disruption lasts longer, the supply chain will experience shortages and profit will be reduced, as shown in Table 6.5 and Figure 6.19. However, the loss in profit will be much less with mitigation.

Table 6.5: Supply chain profit under case 2 (supplier K3 is disrupted)

Disruption	Normal (Reference)	No extra raw material inventory	With extra raw material inventory
Short-term	$ 114,824,444	$ 105,683,067	$ 114,128,893
Medium-term	$ 114,824,444	$ 93,193,650	$ 110,109,507
Long-term	$ 114,824,444	$ 75,438,020	$ 93,363,214

Notice that the supply chain profits during period 3 and 4 are slightly decreased due to the additional inventory holding cost.

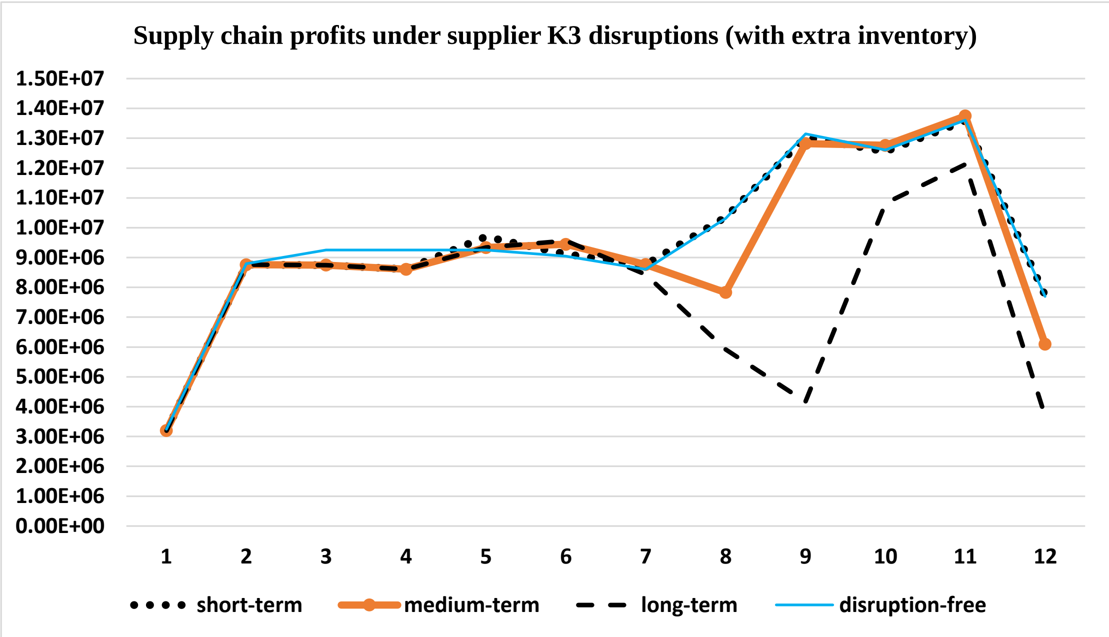


Figure 6.19: Supply chain profits when carrying extra inventory (case 2)

Case 3: Mitigation strategy: having both a backup supplier and carrying raw materials inventory at plant M1

Having both a backup supplier and carrying extra inventory represent the strategy a company might take to mitigate medium-term or a long-term disruptions. Extra inventory enables a supply chain network to continue its operations until a backup supplier is available. In our example, having both a backup supplier and raw materials inventory at plant M1 improve the supply chain resiliency when facing disruption at supplier K3. From Table 6.6, the supply chain profit is $114,427,234 under case 3. In other words, a backup supplier and extra inventory strategy saves about $8.74 million in profit loss, whereas it costs about $0.4 million for short-term disruption. Table 6.6 and Figure 6.20 present a comparison of supply chain profits, which indicate significant improvements to supply chain profits under case 3 for different risk durations. In addition, the supply chain profit returns to its normal condition even before the affected supplier recovers from a disruption.

Table 6.6: Supply chain profit under case 3 (supplier K3 is disrupted)

Disruption	Normal (Reference)	No backup supplier and no extra inventory	With backup supplier and extra inventory
Short-term	$ 114,824,444	$ 105,683,067	$ 114,427,234
Medium-term	$ 114,824,444	$ 93,193,650	$ 113,796,221
Long-term	$ 114,824,444	$ 75,438,020	$ 112,980,479

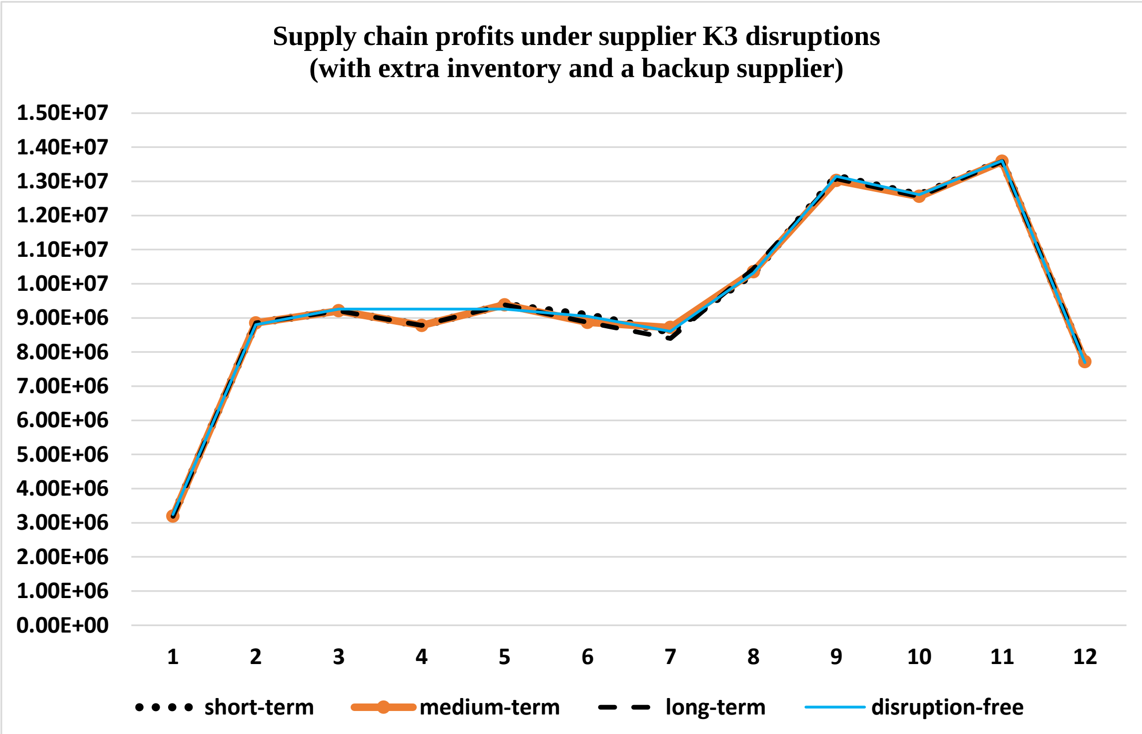


Figure 6.20: Supply chain profits under supplier K3 disruption (case 3)

6.5.3 Further discussion of the risk mitigation results

From the vulnerability analysis and the risk mitigation analysis, we can compare the costs and the benefits of different risk mitigation strategies (cases 1, 2, and 3), as shown in Tables 6.7-6.9. Note that the mitigation cost does not include fixed cost associated with the risk mitigation strategy.

Table 6.7: Impact of mitigation strategies to supplier K3 (short-term disruption)

Risk Mitigation Alternatives	Supply chain profit	Unfulfilled demand	Mitigation cost	Mitigation benefit
A0: Do nothing	$ 105,683,067	4.38%	$ -	$ -
A1: Backup supplier	$ 114,303,080	0%	$ 521,364.60	$ 8,620,013.06
A2: Extra raw material at plant	$ 114,128,893	0%	$ 680,820.62	$ 8,445,826.04
A3: Both A1 and A2	$ 114,427,234	0%	$ 397,210.06	$ 8,744,167.60

Table 6.8: Impact of mitigation strategies to supplier K3 (medium-term disruption)

Risk Mitigation Alternatives	Supply chain profit	Unfulfilled demand	Mitigation cost	Mitigation benefit
A0: Do nothing	$ 93,193,650	10.59%	$ -	$ -
A1: Backup supplier	$ 113,653,738	0%	$ 1,170,706.20	$ 20,460,087.88
A2: Extra raw material at plant	$ 110,109,507	2.07%	$ 680,820.62	$ 16,915,856.39
A3: Both A1 and A2	$ 113,796,221	0%	$ 1,028,222.86	$ 20,602,571.22

Table 6.9: Impact of mitigation strategies to supplier K3 (long-term disruption)

Risk Mitigation Alternatives	Supply chain profit	Unfulfilled demand	Mitigation cost	Mitigation benefit
A0: Do nothing	$ 75,438,020	19.38%	$ -	$ -
A1: Backup supplier	$ 112,836,241	0%	$ 1,988,203.20	$ 37,398,220.80
A2: Extra raw material at plant	$ 93,363,214	10.47%	$ 680,820.62	$ 17,925,193.38
A3: Both A1 and A2	$ 112,980,479	0%	$ 1,843,964.80	$ 37,542,459.20

Based on Tables 6.7-6.9, all the risk mitigation strategies are attractive, as the mitigation costs are less than the mitigation benefits and the supply chain profits are higher than without any mitigation. However, this comparison alone may not be sufficient to evaluate the effectiveness of each risk mitigation strategy. A company may need to consider other costs of the mitigation strategy. For example, carrying extra inventory may lead to excessive holding cost or obsolescence, having a backup supplier requires real-time risk supplier monitoring and an effective communication between organizations. A company should ensure that a backup supplier is capable of providing raw materials when needed at short notice. In some industries, such as electronics and automotive, a supplier qualification process could take several months. Furthermore, a backup supplier strategy may not be always possible. For example, the explosion at a German chemical plant that supplies the PA-12 resin in March 2012 caused panic to the auto industry. The affected German plant was responsible for about one-quarter of the world’s supply of PA-12, and about 70 percent of the world’s cyclododecatriene (CDT), a crucial ingredient in the manufacture of PA-12 (www.apics.org). Chopra and Sodhi (2004) provide general guidelines for assessing impact of mitigation strategies, as shown in Table 6.10.

Table 6.10: Impact of mitigation strategies (adapted from Chopra & Sodhi, 2004)

Mitigation Strategy	Disruptions	Delays	Forecast	Procurement	Receivables	Capacity	Inventory
Add capacity		DD		D		NN	D
Add inventory	D	DD		D		D	NN
Have redundant suppliers	DD			D		N	D
Increase responsiveness		DD	DD				DD
Increase flexibility		DD		D		DD	D
Aggregate or pool demand			DD			DD	DD
Increase capability		D					D
Have more customer accounts					D		

DD : Greatly Decrease Risk NN: Greatly Increase Risk
D : Decrease Risk N : Increase Risk

6.5.4 Decision tree analysis for evaluating risk mitigation strategies

Since the probability of occurrence of a facility or a transportation link disruption is low, companies may want evaluate risk mitigation strategies based on possible disruption outcomes. A decision tree analysis can be applied to analyze the possible consequences of a decision. A decision tree is a chronological arrangement of choices that are controlled by a decision maker and choices that are determined by chance (Raiffa, 1970). A choice by a decision maker is called a decision node, which is usually represented by a square. A choice that is determined by chance is called a chance node, which is represented by circles. Decision tree is a widely used method for supporting decision-making as it clearly layouts the problem, which allows a decision maker to analyze the possible consequences of a decision. It also provides a framework to quantity the monetary values of outcomes to help a decision maker making the best decision based on existing information (www.MindTools.com).

Figure 6.21 presents a decision tree to evaluate two risk mitigation alternatives: carrying extra raw materials inventory and do nothing, in order to reduce the impacts of the supplier K3 disruption.

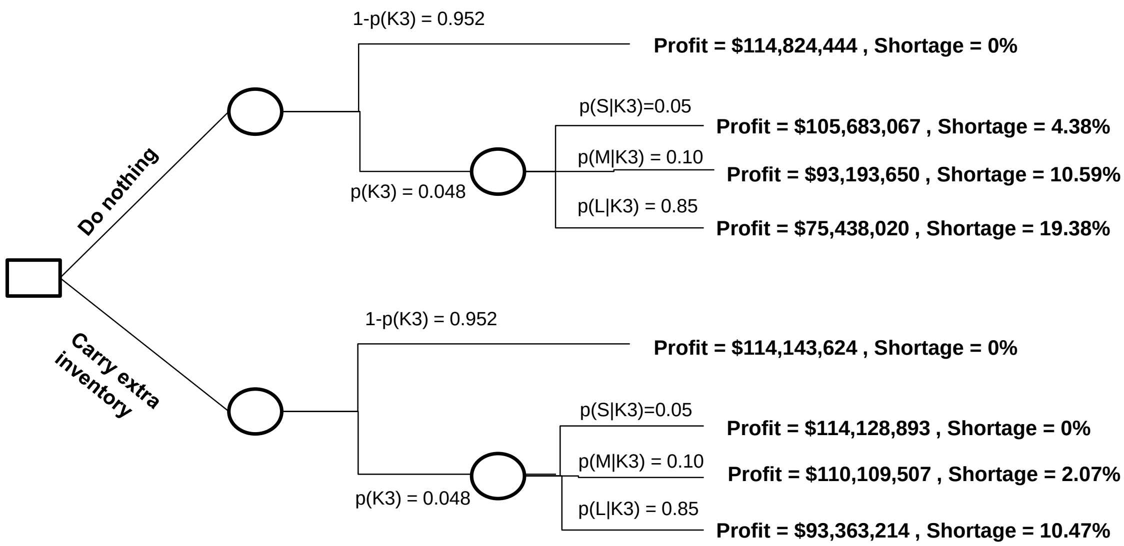


Figure 6.21: Decision tree to evaluate a risk mitigation strategy

Choice nodes are the risk mitigation alternatives: do nothing and carrying extra inventory. Chance nodes are the chance that a supplier K3 disruption does not affect the supply chain operation, and the chance that a supplier K3 disruption affects the supply chain operation. The value p(K3) represents the probability that a supplier K3 disruption affects the supply chain operation, while p(S|K3), p(M|K3), and p(L|K3) represent the probabilities that the disruption-duration is short-term, medium-term, or long-term, respectively. These probability values may be estimated from historical data, expert opinion, or a company's risk management group. Suppose there is no fixed cost associated with the extra raw materials inventory, because the inventory is located at an existing plant facility.

A company estimates the chance that supplier K3 will be disrupted due to floods using data from *the Summarized Table of Natural Disasters in China from 1900 to 2013* (EM-DAT, 2013). China experienced about 147 general floods. In addition, from *Top 10 Natural Disasters in China for the period 1900 to 2013 sorted by economic damage costs* (EM-DAT, 2013), seven floods are identified in this group. Therefore, the company defines p(K3) = 7/147 = 0.048. In addition, supplier K3 is located in a developing country, where disaster preparations are not fully implemented. Hence, if a disruption occurs at supplier K3, it might take several months to fully recover. The chance of the disruption-duration is short-term, medium-term, and long-term are 5%, 10%, and 85%. That is p(S|K3) = 0.05, p(M|K3) = 0.10, and p(L|K3) = 0.85. Therefore, the path probabilities are: p(S∩K3) = 0.048*0.05 = 0.002, p(M∩K3) = 0.048*0.10 = 0.005, and p(L∩K3) = 0.048*0.85 = 0.040. The expected supply chain profit and the expected unfulfilled demand for the "do nothing" and "extra inventory" alternatives are summarized in Table 6.11.

Table 6.11: Comparison between risk mitigation alternatives

Risk mitigation actions	Probability	Do nothing		Extra raw material inventory	
		Profit	Unfulfilled demand	Profit	Unfulfilled demand
No disruption	0.952	$ 114,824,444	0%	$ 114,143,624	0%
Short-term disruption	0.002	$ 105,683,067	4.38%	$ 114,128,893	0%
Medium-term disruption	0.005	$ 93,193,650	10.59%	$ 110,109,507	2.07%
Long-term disruption	0.040	$ 75,438,020	19.38%	$ 93,363,214	10.47%
Expected Value		**$ 113,105,462.64**	**0.85%**	**$ 113,283,266.57**	**0.43%**

Expected profit (Do nothing)

= (0.952*114,824,444) + (0.002*105,683,067) + (0.005*93,193,650) + (0.04*75,438,020)

= $113,105,462.64

Expected unfulfilled demand (Do nothing)

= (0.952*0) + (0.002*4.38) + (0.005*10.59) + (0.04*19.38)

= 0.85%

Using similar calculations for the extra inventory strategy, the expected supply chain profit and the expected demand fulfillment are $113,283,266.57 and 0.43%. The results imply that, even though the occurrence of a disruption risk is very rare, it is worth to have risk mitigation in place to reduce the negative impacts due to a disruption. A decision tree can also be used to evaluate various other risk mitigation alternatives given in Tables 6.7-6.9. It is important to include fixed costs associated with a backup supplier strategy.

A decision to implement risk mitigation strategies may depend on the attitude of a company towards risk. We present the evaluation between two risk mitigation alternatives: having a backup supplier and having both extra inventory and backup supplier by varying the probability of supplier K3 being disrupted, p(K3), from 0 to 1. Figure 6.22 shows that, if p(K3) is less than 0.66, having a backup supplier yields a better expected supply chain profit, otherwise having both extra inventory and backup supplier yields a better expected supply chain profit.

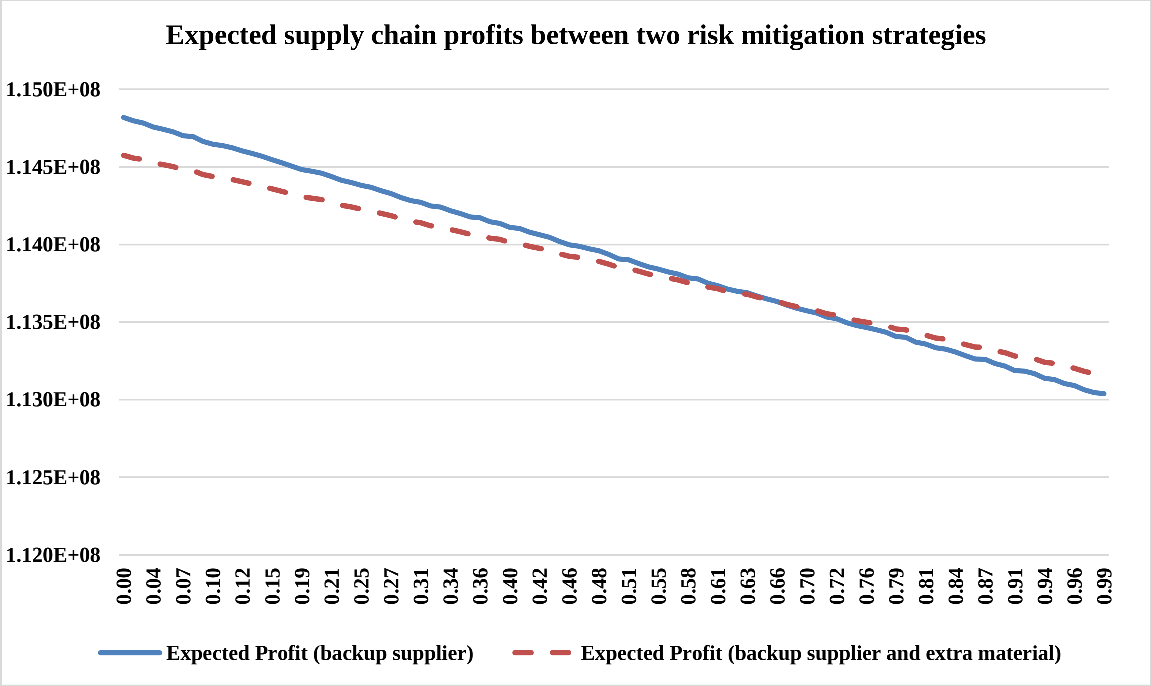


Figure 6.22: Evaluation between two mitigation alternatives

6.6 Conclusion

In this chapter, we demonstrate how to improve the resiliency of an existing supply chain network using a multi-period optimization model. In Sections 6.2, 6.3, and 6.4, we perform a vulnerability analysis to illustrate the level of resiliency in the supply chain network under different disruption scenarios. The impacts of disruptions are presented in terms of the supply chain profit and demand fulfillment. In Section 6.5, we perform a risk mitigation analysis to demonstrate the improvement to supply chain resiliency under different risk mitigation strategies, such as backup supplier and extra inventory. Finally, we apply a decision tree analysis to evaluate the various risk mitigation strategies in conjunction with the probability of occurrence of various disruptions.

Based on the analysis of supplier K3 disruption, all three risk mitigation strategies (use of backup supplier, keep extra raw material inventory, and have both backup supplier and extra inventory) improve resiliency of the existing supply chain network. Having a backup supplier increases resiliency by providing sufficient supply capacity. Keeping extra raw material inventory temporarily prevents part shortages; hence, it is suitable for mitigating a short-term disruption. Having both backup supplier and extra inventory would be appropriate to mitigate medium-term or long-term disruptions. Extra inventory allows a supply chain network to continue its operations until a backup supplier is available. The cost benefit analysis shows all the risk mitigation strategies are attractive as the mitigation costs are much less than the mitigation benefits, and the supply chain profits are also higher than those without any mitigation strategy.

Chapter 7

Summary of the Research and Future Directions

7.1 Summary of the research

This dissertation illustrates how to incorporate disruption risks when making supply chain decisions in order to improve the robustness and the resiliency of a supply chain. Key contributions of this dissertation are:

- A methodology for disruption risk assessment (Chapter 3)
- Multi-criteria supply chain network design model to enhance the robustness of the supply chain network (Chapter 4)
- Multi-period supply chain network tactical model to improve the resiliency of the supply chain network operations through cost benefit analysis of risk mitigation strategies (Chapters 5 and 6).

The first chapter discussed the importance of disruption risks in global supply chains and stated objectives of this research. Chapter 2 provided a literature review on the topics related to the disruption risk management in supply chains. The review included a risk management framework and how to incorporate disruption risks in supply chain decisions, such as supplier selection, facility location, and supply chain network design. From the review, we observed that the research on supply chain risk assessment, which combined both risk analysis and vulnerability analysis, was very limited. That observation motivated the disruption risk assessment presented in Chapter 3.

In Chapter 3, we provided a disruption risk assessment framework to quantity the disruption risk scores for the various supply chain components - facilities and transportation links. Disruption to a global supply chain component depends on hazard (or risk event), vulnerability of a supply chain component (facility or transportation link), and availability of risk management practice to cope with a hazard. The quantified disruption risk values were used to develop a disruption risk profile. We presented a case study by applying the risk assessment framework to a company. The quantified disruption risk values were then used as disruption risk parameters in the supply chain model for designing a global supply chain network in Chapter 4.

Chapter 4 presented a multi-criteria supply chain network design model considering disruption risk. The design criteria were profit, demand fulfillment, delivery time to customers, facilities disruption risk, and transportation links disruption risk. We solved the problem using preemptive (P-GP) and non-preemptive (NP-GP) goal programming approaches to handle the multiple and conflicting design criteria. For a NP-GP, we used a simple rating method and AHP to determine weights. The P-GP and NP-GP solutions showed that a supply chain network design that primarily focused on profit and customer satisfaction would select inexpensive facilities and transportation links, which might have high disruption risk values. By incorporating disruption risk as one of the design criteria, the supply chain design solutions consist of low-risk facilities and low-risk transportation links, resulting in a more robust supply chain network. The goal programming solutions also provided the tradeoff between multiple objectives, such as, the improvement in disruption risk value at the expense of supply chain profit. We used the value path approach (VPA) to visually display the tradeoff among different objectives for the P-GP and NP-GP solutions.

Even though risk minimization is one of the supply chain design criteria, disruption risks still exist. Disruption may occur at any supply chain component at any time during a planning horizon. This fact led to the study in Chapters 5 and 6. The supply chain network design solution was subjected to a vulnerability analysis and a risk mitigation analysis. Chapter 5 provided a mixed-integer linear programming model to support a multi-period tactical decision-making for a supply chain network obtained from Chapter 4. The tactical model provided medium-term decisions that included raw materials purchasing plan, production plan, distribution plan, and inventory level. The objective was to maximize the supply chain operation profit. We solved the model assuming no disruption during the planning horizon. The optimal solution represented the disruption-free scenario, which was then used as a baseline for improving the supply chain network resilience in Chapter 6.

Chapter 6 consisted of vulnerability analysis and risk mitigation analysis. The vulnerability analysis demonstrated the resiliency of the supply chain network operations under disruptions to a supply chain component. The disruption was incorporated in the mathematical model by changing the binary parameter value corresponding to the affected supply chain component from one to zero, and then re-optimizing the tactical model. Since a disruption might cause product shortages, we modified the model objective from maximizing profit to minimizing the negative deviation of the supply chain profit and the negative deviation of the minimum demand fulfillment. We provided a numerical example to show the tradeoff between these two objectives. Finally, the risk mitigation analysis was used to evaluate the effectiveness of risk mitigation strategies, such as a backup supplier and extra inventory. The analysis was also used to study the cost benefits of different risk mitigation strategies. We demonstrated that the risk mitigation strategies help improve the resiliency of the supply chain network under disruptions.

7.2 Key Contributions

The major contributions of this research are the following:

i) From a practical perspective, the assessment framework can serve as a useful guideline for practitioners to quantify disruption risk in their supply chains and to facilitate the development of risk mitigation strategies. The consideration of hazard, vulnerability, and risk management practice also enables companies to better understand their business partners. In addition, the quantified disruption risk score can be used to construct a disruption risk matrix, which is beneficial for companies in prioritizing the risk events and selecting appropriate mitigation strategies. The case study demonstrated the feasibility of using the risk assessment framework by practitioners.

ii) From a research perspective, most of the supply chain risk management literature assess the disruption risk (e.g., natural and man-made disasters) based on its occurrence and impact. In this study, we assess the risk based on the hazard, the vulnerability of a supply chain component, and the availability of risk mitigation practices. In addition, we assess separately the disruption risk of supply chain entities (facilities) and transportation links.

iii) The multi-criteria supply chain strategic model considering disruption risk can be used to design a robust supply chain network.

iv) The multi-period supply chain tactical model can be used to evaluate the vulnerability of an existing supply chain network, to improve the resiliency of a supply chain network operation, and to determine the cost benefits of risk mitigation strategies.

7.3 Future Research Opportunities

i) The disruption risk assessment is a qualitative assessment process, which is based on a single decision maker's attitude towards risk factors and their attributes. In practice, the assessment should involve a cross-functional team. The qualitative assessment could be improved by considering multiple decision makers and the ambiguity of a qualitative assessment. In addition, more elaborate quantitative of risk occurrence and impact models can be developed for critical risk events using extreme value distributions given in Bilsel and Ravindran (2012).

ii) The multi-criteria supply chain network design model in Chapter 4 enhances the robustness of a supply chain network by choosing low-disruption risk facilities and low-disruption risk transportation links. However, the designed network may not be resilient due to a lack of redundancy in the network structure. Future work can modify the model by adding redundancy (e.g., backup facility or backup transportation) or diversifying risk (e.g., multiple suppliers, multiple transportation links) in order to reduce the impact from a disruption.

iii) Both the supply chain strategic model (Chapter 4) and the supply chain tactical model (Chapter 5) assume deterministic demand, cost, and lead-time. Future work may include uncertainties in these parameters.

iv) In the vulnerability analysis, each disruptive scenario considers the disruption of only one supply chain component. In practice, multiple facilities or transportation links could be disrupted at the same time. Future work may extend the vulnerability analysis by considering the disruption of multiple supply chain components.

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