The Pennsylvania State University

The Graduate School

College of Engineering

ANALYSIS OF SUPPLY CHAIN RISK VULNERABILITY AND MITIGATION STRATEGIES

A Thesis in

Industrial Engineering

by

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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

August 2015

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ABSTRACT

Based on a combined inventory and transportation model considering disruption risks for a four-stage global supply chain, this thesis focuses on supply chain network vulnerability and risk mitigation strategies. We use the READI (Resiliency Enhancement Analysis via Deletion and Insertion) method to improve supply chain resiliency. First, we use preemptive goal programming and non-preemptive goal programming methods to solve the baseline mathematical model under no disruptions. Then we generate several disruption scenarios of critical facilities and transportation links based on historical records. According to these disruption scenarios and corresponding disruption duration, we estimate the effect of disruption and the vulnerability of chosen nodes and links with respect to changes of the three objectives (profit, backorders and risk). For each node and link, we consider one specific risk mitigation strategy, such as keeping extra inventory, using backup supplier, purchasing insurance, and use of alternative transportation mode to illustrate how the resiliency can be improved for a supply chain network. After re-optimizing the model, we get the changes in each objective compared to the baseline optimization results. Comparing the results, with and without mitigation strategy, the cost benefits of a mitigation strategy is determined.

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ACKNOWLEDGEMENTS

I would like to thank Dr. A. Ravindran sincerely for his patient help and professional guide, and I learn much from the procedure of writing thesis. Also, I would like to thank Dr. Harrison for being my thesis reader and spending much time in revising my thesis. Special thanks are due to Xin Dai and Yuan Wang for checking, correcting my LINGO code and modifying my mathematical model. I also thank my family members for their support.

Chapter 1

Introduction

1.1 Introduction

During the early years of the 21st century, there were several major supply chain disruptions which caused heavy losses. These disruptions not only damaged domestic industries but also affected the world economy due to globalization. In addition to taking many lives, the Japanese tsunami in 2011 caused mass destructions in business and industry operation. For example, almost one-fifth of the international semiconductor industry is dominated by Japan. Thailand's 2011 floods affected the supply chains of computer manufacturers dependent on hard disks and of Japanese auto companies with plants in Thailand. The 2010 eruption of a volcano in Iceland disrupted millions of air travelers and affected time-sensitive air shipments (Chopra and Sodhi, 2012).

Managers have already realized the importance of protecting their supply chains from serious and costly disruptions. To address this problem, simple solutions, such as increasing inventory, adding capacity at different locations and having multiple suppliers have been proposed. However, these actions will increase the cost of whole supply chain. 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 (Ravindran and Warsing, 2013). They have offered detailed methodology for managing the supply chain risk.

There are many risk quantifications approaches. A common approach is to determine the risk index, and include it as a criterion in the supply chain model. 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 and Sokolov, 2012).

1.2 Background

1.2.1 Global Supply Chain Management

Supply chain management (SCM) as a field is approximately 25 years old, but the traditional business functions in SCM (i.e., procurement, forecasting, production, transportation, warehousing, customer service, and order management) have been around since business began. The Council of Supply Chain Management Professionals (CSCMP) defines supply chain management as: "Encompass the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-party service providers, and customers". In essence, Supply Chain Management integrates supply and demand management within and across companies.

According to the U.N. Economic and Social Commission for Western Asia, globalization in an economic context, refers to the "reduction and removal of barriers between national borders in order to facilitate the flow of goods, capital, services and labor". Globalization was facilitated by the existence of World Trade Organization, and the barriers to global trade decreased. Figure 1.1 illustrates the growth in international merchandise trade during 1980-2010.

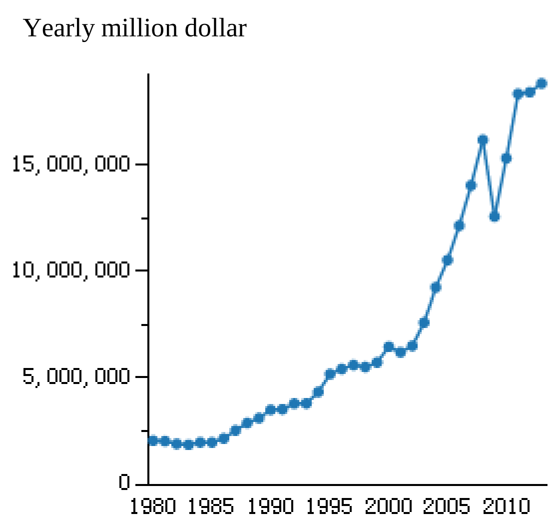

Figure 1.1 International Merchandise Trade

Globalization provides companies with opportunities to enter new markets, find better suppliers and take advantage of cheaper labor available in other countries. However, man-made and natural disasters could damage the global supply. There are three big challenges in managing global supply chains: required resources, recruitment and retention of local talent and integration of IT systems (McKinsey survey, 2008). That's why we need global supply chain strategies. According to Simchi and Simchi (2003), global supply chains can have many forms and shapes and they fall into one of the following types:

- Global distribution: Manufacturing is done mainly in one country and the products are distributed worldwide.
- Global suppliers: International vendors supply raw materials and parts, but the final assembly and manufacturing are done domestically.
- Offshore manufacturing: The product is manufactured in a foreign location, imported back and distributed locally to customers.
- Integrate global supply chain: Here raw materials are sourced from some countries, sub-assemblies and final assemblies are done in other countries and final products are distributed using distribution centers in several countries.

International logistics, which is defined as the movement of goods across national boundaries, is also important. Managing international logistics is a complex process. It involves multiple parties handling the goods. Nowadays companies are increasing the flexibility of the logistics networks for transporting their products. They reduced the number of carriers, logistics providers and IT systems. They also increased visibility at the suppliers, used flexible transportation modes, practiced co-mingling of shipments with other companies and product postponement strategies. Postponement involves the practice of making the product differentiation as close to the customer as possible.

For managers, there is always a tradeoff between supply chain efficiency and responsiveness. For instance, choosing air transportation mode means less time and more responsiveness, but will increase cost. Mathematical models can analyze these tradeoffs.

1.2.2 Risk Management in Supply Chain

Risk is the combination of the probability of an event and its consequence/impacts. Risk in the context of supply chains may be associated with the production/procurement process, the transportation/shipment of the goods, and the demand market. Risks need to be categorized and different strategies should be developed.

Given the importance of supply chain management, companies already have their respective organizations in place to carry out the supply-chain activities that entailed. Therefore, it makes sense to categorize risks in a way that follows the supply chain organization. This way, different entities within the supply chain organization can identify those who are best positioned to prevent or contain the consequences of certain types of risks events and who should be responsible for managing the corresponding risk categories. Sodhi and Tang (2012) categorize the different kinds of supply chain risks and list the organizations of each category as shown in Table 1.1.

Table 1.1 Supply Chain Risk Categorization Motivated by the Supply Chain Organization (Sodhi and Tang, 2012)

Types of risks	**Supply chain organization**	**Example and reason**
Supply risks	Supplier failure	The bankruptcy in 2001 of UPF-Thompson, sole classis supplier to Land Rover, which caused major problems for the auto maker
	Supply commitment	If the buying organization has to commit to long-term purchase from its supplier without the option of revising the quantities, it can have the risk of having unmet demand or excess inventory over time
	Supply cost	This refers to unanticipated increase in acquisition costs resulting from supplier price hikes or from fluctuating exchange rates
Process risks	Design	Toyota's recall of cars in late 2009 and early 2010 owing to "sticky" accelerators has hurt the company's reputation, demand and stock price
	Yield	If the manufacturing yield at a plant is uncertain, it can result in the company not being able to match its supply to its demand
	Inventory	The extent of the risk stemming from inventory depends on the value of the product, its rate of obsolescence, and uncertainty of demand or of supply
	Capacity	Building excess capacity is usually a strategic choice as it may take much longer to ramp capacity up or down compared to changing inventory levels and may cost a lot more
	Forecasting	Forecast risk stems from the mismatch between a company's forecast and actual demand. Forecast error also result from information distortion with the supply chain
	Change in technology or	The electronics industry is constantly buffeted by new technology or designs and Apple 's 2010 introduction of the

Demand risks	customer preference	iPad left competitors such as Amazon's Kindle scrambling for comparable offerings or having to offer price reduction
	Receivable	Inability to collect on receivables. In 2002, Sears Roebuck's credit division reported unexpected losses caused by delinquent cardholders
Corporate-level risk	Financial	When a company is expanding markets, the goal is market share, along with other objective and subjective measures. Another issue related to conglomerates is shareholder interest translating to cash injections to keep some companies within the conglomerate afloat in difficult times
	Supply chain visibility	As the number of partners increases in a global supply chain, the level of visibility and control can be reduced significantly
	Political/social	For example, airbus, a four-nation consortium, incurred an opportunity cost of 4.8 billion euros due to a two-year delay in launching the super-jumbo A380
	IT systems	A breakdown of information infrastructure can devastate efficient network in supply chain nodes
	Intellectual property	While outsourcing or offshoring to low-cost countries does lower the cost of goods sold, the company can become more vulnerable to loss of its intellectual property
	Exchange rate	This type of risk can be countered by creating financial hedges, balancing cost and revenue flows by region, and building flexible global capacity

1.2.3 Risk Management Strategy

Elkins et al (2008) recommend the use of a cross-functional team of experts to brainstorm and develop the risk portfolio. The next step is risk assessment, which is risk mapping and risk prioritization. Risk mapping is a subjective process where the risks are broadly classified based on risk occurrence and risk impact. Developing a risk map provides a quick and easy way to identify and focus on critical risks. Then ranking the risks in the various squares. Ravindran and Warsing (2013) presents a simple risk scoring method, which is using risk priority numbers (RPN) to rank the critical risks or at least identify the top 10 or 20 risks that need attention.

$$\text{RPN} = (\text{occurrence})(\text{impact})(\text{detection})(\text{recovery})$$

Risk management strategies can be broadly grouped into three categories as follows:

- Risk Mitigation

  Risk mitigation is taking intervention strategies according to the product design, manufacturing and supply chain operations to reduce or eliminate risks.

- Contingency Planning

  When the risk is identified, there should be preplanned actions. If risk happens, certain resources could be made available at short time to fix problems, for instance, having "back up" suppliers.

- Business Insurance

  Purchasing business insurance in advance helps to cover the financial loss due to business interruptions caused by natural and man-made disasters. However, the price is high as well, and only financial loss will be covered. Insurance does not cover stock prices, market share and negative impact on brand name.

1.3 Plan of Research

This thesis is an extension of the master's thesis by Rahavan (2013). He considers a four-stage centralized supply chain. The stages are connected by four modes of transportation (air, road, rail and ocean). His thesis developed an optimization model to determine what quantity of the total demand should be allotted to each unit in each stage and which transportation route should be chosen to minimize cost, maximize responsiveness and minimize total disruption risk.

1.3.1 A Baseline Optimization Model

Consider a four-stage supply chain network. A centralized supply chain is one where all the stages are owned by the same company. Figure 1.2 illustrates a four stage supply chain with three suppliers, two manufacturers, two warehouses and three retailers with four modes of transportation (air, road, rail and ocean) between the stages.

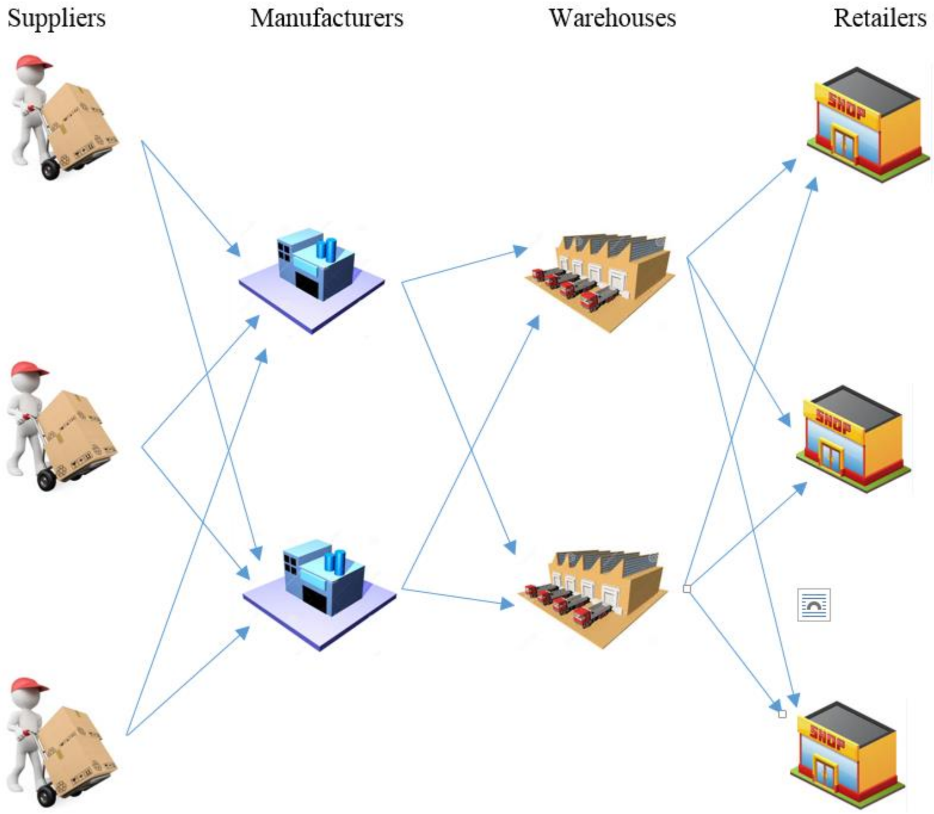

Figure 1.2 Four-Stage Supply Chain Network with Four Modes of Transportation between Stages

Using forecasted demand, pre-determined risk scores of nodes and links, capacity of production and inventory, and prices of production, purchasing and transportation, we determine:

- Which transportation mode should be chosen and the quantity of products or raw materials for each link under each transportation mode.
- What quantity of product should be produced in each manufacturer and what quantity of inventory is optimal in order to maximize the profit, minimize the backorder and minimize disruption risk.

To quantify the risk scores, two kinds of disruption risk scores are developed: node risk score and link risk score. Specifically, node risk scores come from historical data of supplier, manufacturer, distributor and retailer, and link risk scores deal with risks related to the transportation mode used between nodes. These risk indices have been computed using Rating method, Pair-wise comparison and Analytical Hierarchy Process as given in the thesis of Rahavan (2013). Essentially, we view the mathematical model in Rahavan's thesis as the base model, with no disruptions at the nodes or links.

1.3.2 Vulnerability Analysis

Vulnerability analysis demonstrates the implications of a supply chain component disruption to the supply chain profit and quantity of backorder. The aim of the thesis is to focus on the supply chain network's vulnerability and analyze risk mitigation strategies. For this, we use the Resiliency Enhancement Analysis via Deletion and Insertion (READI) method presented by Harrison et al. (2013) to improve supply chain resilience. Firstly, we solve the mathematical model developed in Section 1.3.1 to get baseline optimal solutions. The disruption-free planning is then subjected to a disruption of a supply chain network component (a node or a transportation link). The occurrence of a disruption, disruption-duration and disruption impact are different depending on the risk event and the affected node or link's vulnerability. Here we assume that a disruption occurs at the beginning of a planning horizon, and the disruption-durations are one and two weeks. Then a single node or link is removed from the supply chain network and the supply chain is re-optimized. This step allows for an assessment of the impact of the removed node or link. In this thesis, we need to generate several disruption scenarios based on historical records of critical facilities and transportation links. We assume that each node or link is vulnerable to one specific potential risk, like earthquake or flood. According to these disruption scenarios and corresponding disruption duration, we estimate the effect of disruption and the vulnerability of the supply chain through the change in each objective (profit, backorders and risk).

1.3.3 Risk Mitigation Strategies

Here we study the cost benefits of risk mitigation strategies to demonstrate the improvement to the supply chain performance. We incorporate one specific risk mitigation strategy for each node and link, such as a backup facility for manufacturer or extra inventory for distributor or use of alternative transportation mode, to illustrate how the resiliency can be improved for a supply chain network. We also study the tradeoff between mitigation cost and improved profit or lower quantity of backorder. In this thesis, 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, which depends on the mitigation strategy. We assume that the raw materials costs from a backup supplier are higher than those from a regular supplier.

1.4 Structure of the Thesis

Chapter 2 of this thesis will include a comprehensive review of the related areas, including vulnerability analysis in supply chain and disaster risk management. In Chapter 3, the calculation of risk scores and the baseline optimization model will be presented. Then a set of possible risk situations will be considered to evaluate the impact of supply chain disruptions to the supply chain network performance. Then we apply potential risk mitigation strategies to study the improvement to the supply chain performance. In Chapter 4, a numerical example will be presented and solved by multi-criteria optimization methods. Then, according to possible risk situations, we get the effect of disruption at chosen nodes and links. We then compare those solutions before using mitigation strategies to optimal solutions after using mitigation strategies to study their benefits. Chapter 5 will conclude with the summary and suggestions for future work.

Chapter 2

Literature Review

In this chapter, some of the articles from the literature in vulnerability analysis in supply chain and disaster risk management are discussed in detail. Section 2.1 deals with articles which are related to vulnerability analysis in supply chain, and section 2.2 summarizes articles about disaster risk management.

2.1 Vulnerability Analysis

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 (Asbjornslett, 1999). In other words, vulnerability focuses on the efficiency and adequacy of the available resources to mitigate the system from disruptions (Kungwalsong 2013).

Warner et al (2003) says that vulnerability studies estimate the physical, social, and economic consequences that result from the occurrence of a natural phenomenon of given severity. Physical vulnerability studies are impacts on buildings, infrastructure, and agriculture. Social vulnerability studies take into account the public awareness of risk, the ability of groups to self-cope with catastrophes, and the institutional structures in place to help them cope.

Supply chain vulnerability has been defined broadly by Christopher and Peck (2004) as "an exposure to serious disturbance" and by Jüttner et al (2003) as "the propensity of risk sources and risk drivers to outweigh risk mitigating strategies, thus causing adverse supply chain consequences". There are a large number of studies related to supply chain vulnerability, however, most of them present conceptual frameworks.

Weichselgartner (2001) suggests that the concept of vulnerability can provide a vehicle to explore a contextual approach to the reduction of losses due to natural hazards. Even without assessing risk exactly, vulnerability reduction decreases damages and losses.

Svensson (2000) develops a conceptual framework for the analysis of vulnerability in supply chain, which is limited to the inbound logistic flow of manufacturers. The study includes two steps. The first step generates the conceptual framework based on the empirical findings from a case study, and the second step is deductive in terms of testing in other industries the generated conceptual framework that originates from step one. Categories of disturbance and sources of disturbance consist of the conceptual framework. Furthermore, categories of disturbance are divided into quantitative and qualitative disturbances, and sources of disturbance are divided into direct and indirect disturbances.

2.2 Disaster Risk Management

2.2.1 Qualitative risk in supply chain

As a result of changes in the economic and business environments, modern supply chains seem to be more vulnerable than ever before. There are many reasons. First, disasters have increased in number and in intensity during the last decade. Second, today's supply chains are more complex than they used to be. There are various reasons for supply chain complexity, such as manufacturing outsourcing, supplier to supplier relationships in supplier network, and shorter product life-cycles due to rapidly changing customer preferences, international market and production expansion. Third, with competition becoming fierce, competitive pressures often force companies to assume more "calculated risk" – risks that managers must accept in order to improve competitiveness, reduce costs and improve profitability. However, the downside of the "calculated risk" is adverse consequences that jeopardize the whole supply chain's ability to serve the final customers, thus affecting firm's long-term goal accomplishment (Svensson, 2002).

Craighead et al (2007) focus on a relatively unexplored issue, asking and answering the question of how and why one supply chain disruption would be more severe than another. The severity of a supply chain disruption can be defined as the number of entities within a supply network whose ability to ship and/or receive goods and materials has been hampered by an unplanned, unanticipated event. The severity of a supply chain disruption within a supply chain appears to be positively related to supply chain density. A second and related factor contributing to how severe a supply chain disruption might potentially be is supply chain complexity, and complexity is positively related to supply chain disruption. The third is node criticality, which is defined as the importance of a node within a supply chain. Also criticality is positively related to supply chain disruption.

2.2.2 Quantifying supply chain disruption risk

Wang et al (2008) develop an integrated risk index for multiple natural disasters in urban areas. To calculate an overall disaster risk index the authors integrate risk estimates of multiple hazards, including floods, earthquakes, typhoons, landslides and sandstorms, with indices describing urbanization and infrastructure levels. With this index, they classify regions in China according to their exposure to major disaster.

Schmitt and Singh (2009) build model to assess vulnerability to disruption risk and quantify its impact on customer service. Risk profiles for the locations and connections in the supply chain are developed using Monte Carlo simulation, and the flow of material and network interactions are modeled using discrete-event simulation. They build flexibility into the model through variable inputs that allow analysts or company members to test the impact of different parameters, such as customer behavior, disruption probabilities, back-up response times, etc. They also model various strategies for coping with the risk in the system in order to maintain product availability to the customer.

Yang (2007) develops a mathematical model to quantify supply risks. Supply risks are classified into two categories based on their characteristics for quantification purposes: VaR type and MtT type. VaR-type risks are rare and often caused by sudden events, but have significant impact on the Supply Chain. MtT-type risks happen frequently but have less impact. MtT-type risks could be controlled, but may not be totally eliminated for economic reasons, while VaR-type risks are uncontrollable. According to the general definition of risk, risk functions are developed for each type. For VaR-type risks, generalized extreme value (GEV) distribution is recommended for the hazard function. The MtT type is classified into three sub-types: S-type, N-type and L-type. Using Taguchi's loss function, Yang (2007) generates the general S-type, N-type and L-type hazard functions. Gamma distribution is recommended for S-type exposure function, generalized hyperbolic distribution is recommended for N-type exposure function, and Beta distribution is recommended for L-type exposure function.

Bilsel (2009) provides quantitative techniques to measure outsourcing risks and mathematical models to incorporate risks in supply chain decision making. Outsourcing risks are grouped under two main categories: operational risks and disruption risks. He presents a general risk quantification scheme and a classification based on four major risk components: severity of impact, frequency of occurrence, detection time and recovery time. Severity of impact is modeled using the Generalized Extreme Value Distribution. Frequency of occurrence is modeled as a Poisson process.

2.2.3 Supply Chain Network Risk Management and Modeling

Amendola et al (2008) define integrated disaster risk management as a process for comprehensively and credibly estimating and managing risks from multiple synergistic sources. Integrated disaster risk management not only requires rigorous and multi-factor risk assessment, but also calls for procedures and institutions that credibly reduce the risks. Experience shows that knowledge, regulations, codes, and other policy measures are of little use without effective implementation (Wisner, 2004).

Warner et al (2003) divide the key elements of risk management into two phases: the pre-disaster phase and the post-disaster period. The pre-disaster phase includes risk identification, risk mitigation, risk transfer and preparedness; the post-disaster phase is devoted to emergency response, rehabilitation and reconstruction.

The paper written by Klibi and Martel (2012) provides a risk modeling approach to facilitate the evaluation and the design of Supply Chain Networks (SCNs) operating under uncertainty. Three event types are defined to describe plausible future SCN environments: random, hazardous and deeply uncertain events. A three-phase hazard modeling approach is also proposed. It involves a characterization of SCN hazards in terms of multi-hazards, vulnerability sources and exposure levels; the estimation of incident arrival, intensity and duration processes; and the assessment of SCN hit consequences in terms of damage and time to recovery. Based on these descriptive models, a Monte Carlo approach is then proposed to generate plausible future scenarios. This approach enhances the resilience of the designs obtained and it provides superior risk mitigation capabilities. Moreover, the approach provides a valuable SCN design evaluation tool. When a number of candidate designs are available, a large set of Monte-Carlo and worst-case scenarios generated with their approach can be used to evaluate key performance measures, including expected value added, coherent risk metrics and resilience indexes reflecting decision-makers aversion to disruptive events.

2.2.4 Disruption Mitigation Strategy

There is a special case presented by Tomlin (2006) which contains two suppliers, and one of them is more reliable but more expensive. A supplier's percentage uptime and disruption length are key determinants of the optimal strategy. Contingent rerouting is often a component of the optimal disruption-management strategy, and it can significantly reduce the firm's costs. Sourcing mitigation, inventory mitigation, and contingent rerouting are the supply-side tactics to a firm. He illustrates that volume flexibility enables contingent rerouting to be an element of the firm's cost, and can significantly reduce the firm's strategy. Volume flexibility provides an alternative to inventory in managing temporary imbalances in supply and demand.

Kungwalsong (2013) builds a tactical model which enables the resiliency improvement of an existing supply chain network. She uses all three risk mitigation strategies (use of backup supplier, keep extra raw material inventory, and have both backup supplier and extra inventory) to 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.

Harrison et al (2013) propose an approach called READI to improve the resiliency of supply chain. They build four scenarios, the first set of analyses examines the implications of facility disruptions, when no new DCs can be added to the network, and in the second scenario, some of the candidate DCs can be opened, but existing facilities must remain open. The third scenario examines the impact of disruptions when the model is permitted an unconstrained reconfiguration of DCs, while the fourth scenario investigates the mitigation effect of production flexibility. The numerical results are illustrated through the percentage change of missed demand and cost change when no demand is missed.

2.3 Basis for this thesis

This thesis is an extension of Rahavan's (2013) Master's thesis. He develops a multi-period model that has three objectives – Maximize profit, minimize backorder and minimize risk. Disruption risk indices are developed for each site and each link using Borda Count, AHP and Rating method. The model assumes multiple modes of transportation between stages and different lead times for each. Constraints in the model include demand at the retailer, capacity constraints at different stages and the transportation modes, quantity discount constraints, inventory balance constraints, etc. He also considers the number of units of each raw material that is required to build the final finished product. The model gives the shipment quantities for each time period through each transportation mode. The model is solved using preemptive and non-preemptive goal programming methods.

This thesis adds vulnerability analysis for a supply chain network which is solved by Rahavan (2013) and applies disruption mitigation strategy for each disruption scenario. The methods to generate disruption scenario and how to do vulnerability analysis will be discussed in the next chapter. Table 2.1 gives a summary of related research and the contributions of this thesis for comparison.

Table 2.1 Summary of Articles Related to this Thesis

	Article	Topic	Main content
Qualitative risk in supply chain	Svensson (2002)	Reasons for more supply chain vulnerability	Disasters are more intense, supply chains are more complex and companies assume more "calculated risk"
	Craighead et al (2007)	Define the severity of a supply chain disruption	Severity could be defined as the number of disrupted entities; Severity is positively related to supply chain density and complexity
Quantifying supply chain disruption risk	Wang et al (2008)	Develop an integrated risk index for natural disasters in urban areas	Done by the Model-Tupu (map series) and inter-feedback process using digital map technology
	Schemitt and Singh (2009)	Build a model to assess vulnerability and quantify its impact	Risk profiles are developed by Monte Carlo simulation; Flows of material are modeled using discrete-event simulation
	Yang (2007)	Quantify supply risks	Supply risks are classified into VaR-type and MtT-type, then get hazard functions according to their own distributions
	Bilsel (2009)	Quantify outsourcing risks and incorporate risks in supply chain decision making	Classifies risks into operational risks and disruption risks; Generalized Extreme Value Distribution and Poisson process are used in presenting a general risk quantification scheme
Disruption mitigation strategy	Tomlin (2006)	Set a specific supply chain case and study mitigation and contingency strategies	A supplier's percentage uptime and the nature of the disruptions are key determinants of the optimal strategy; contingency rerouting and volume flexibility are used as mitigation strategies
	Kungwalsong (2013)	Do a vulnerability analysis and risk mitigation assessment to evaluate the resiliency of the supply chain under disruptions	Uses risk mitigation strategies such as extra inventory, backup supplier and both to increase the supply chain network resilience
	Harrison et al (2013)	Introduce a method called resiliency enhancement analysis via deletion and insertion (READI) to let companies build and maintain resilience	Build four scenarios and use mitigation strategies, such as adding a new DC and production flexibility
	This thesis	Use READI method to do vulnerability analysis of supply chain and use mitigation strategies to improve resilience	Apply risk mitigation strategies such as keeping extra inventory at distributor, holding backup supplier, purchasing insurance and using other transportation mode

Chapter 3

Vulnerability Analysis and Risk Mitigation for a Supply Chain

3.1 Problem Statement

First we develop a multi-period, multi-objective mathematical model for a four-stage supply chain network considering disruption risks based on the work of Rahavan (2013). Then we focus on the vulnerability and resiliency of supply chain through READI (Resilience Enhancement Analysis via Deletion and Insertion) method of Harrison et al (2013). The objective of the thesis is to develop effective risk mitigation strategies before the disruptions happen.

3.2 Model Formulation

3.2.1 Assumptions

- The supply chain is centralized.
- There are four modes of transportation between stages (Air, Rail, Road and Ocean).
- Backorders are allowed only at the retailers.
- All the units shipped to the retailers in a time period are sold out.
- Finished goods are immediately shipped to the distributors. No finished product inventory is held at the manufacturer.
- For the transportation modes, no quantity discounts are assumed. Total cost is the product of the number of containers and cost per container.
- The forecasted of demands for each period and the cost of shipping are assumed to be known.
- Allow different kinds of raw materials, but only one finished product.
- Initial quantity of backorder at all retailers is assumed to be zero.

3.2.2 Indices

s – Suppliers, s=1, 2, … , S

m –Manufacturers, m=1, 2, … , M

d – Distributors, d=1, 2, … , D

r – Retailers, r=1, 2, … , R

t – Time period, t=1, 2, … , T

n – Raw materials type, n=1, 2, … , N

i – Mode of transportation, i=1 (Air), i=2 (Road), i=3 (Rail), i=4 (Ocean)

3.2.3 Input Parameters

S – No. of suppliers

M – No. of manufacturers

D – No. of distributors

R – No. of retailers

T – No. of time periods

N – Numbers of raw materials

SP – Selling price of one unit of finished product

PC – Cost of producing one unit of finished product

MIC_{nm} – Inventory holding cost per raw material ‘n’ per period at manufacturer ‘m’

DIC_{d} – Inventory holding cost per finished product per period at distributor ‘d’

LT_{m} – Production lead time at manufacturer ‘m’

a_{n} – No. of units of raw material ‘n’ needed to produce one unit of finished product

RMC_{ns} – Cost of procuring one unit of raw material ‘n’ from supplier ‘s’

RS_{st} – Risk index of supplier ‘s’ during time period ‘t’

RM_{mt} – Risk index of manufacturer ‘m’ during time period ‘t’

RD_{dt} –Risk index of distributor ‘d’ during time period ‘t’

$RTSM_{smit}$ –Risk index of transportation mode ‘i’, linking supplier ‘s’ to manufacturer ‘m’, during time period ‘t’

$RTMD_{mdit}$ – Risk index of transportation mode ‘i’, linking manufacturer ‘m’ to distributor ‘d’, during time period ‘t’

$RTDR_{drit}$ – Risk index of transportation mode ‘i’, linking distributor ‘d’ to retailer ‘r’, during time period ‘t’

$MCAP_{m}$ – Capacity of raw material inventory at manufacturer ‘m’

$PMCAP_{m}$ – Capacity of production at manufacturer ‘m’

$DCAP_{d}$ – Capacity of finished product inventory at distributor ‘d’

$SMMAX_{ism}$ – Maximum quantity of containers that can be shipped from supplier ‘s’ to manufacturer ‘m’ through mode ‘i’

$MDMAX_{imd}$ – Maximum quantity of containers that can be shipped from manufacturer ‘m’ to distributor ‘d’ through mode ‘i’

$DRMAX_{idr}$ – Maximum quantity of containers that can be shipped from distributor ‘d’ to retailer ‘r’ through mode ‘i’

DEM_{rt} – Forecasted demand for retailer ‘r’ during time period ‘t’

A_{ism} – Lead time from supplier ‘s’ to manufacturer ‘m’ through mode ‘i’

B_{imd} – Lead time from manufacturer ‘m’ to distributor ‘d’ through mode ‘i’

C_{idr} – Lead time from distributor ‘d’ to retailer ‘r’ through mode ‘i’

CAIR – Cost of shipping one container through air

CROAD – Cost of shipping one container through road

CRAIL – Cost of shipping one container through rail

COCEAN – Cost of shipping one container through ocean

CPAIR – Capacity of a container for air transportation

CPROAD – Capacity of a container for road transportation

CPRAIL – Capacity of a container for rail transportation

CPOCEAN – Capacity of a container for ocean transportation

MEI_{nm} – Inventory of raw material ‘n’ at manufacturer ‘m’ at the end of planning horizon

DEI_d – Inventory of finished product at distributor ‘d’ at the end of planning horizon

MII_{nm} – Initial inventory of raw material ‘n’ at manufacturer ‘m’

DII_d – Initial inventory of finished product at distributor ‘d’

3.2.4 Decision variables

X_{nsmit} – Quantity of raw material ‘n’ shipped from supplier ‘s’ to manufacturer ‘m’ using mode ‘i’ in period ‘t’

Y_{mdit} – Quantity of finished product shipped from manufacturer ‘m’ to distributor ‘d’ using mode ‘i’ in period ‘t’

Z_{drit} – Quantity of finished product shipped from distributor ‘d’ to retailer ‘r’ using mode ‘i’, in period ‘t’

D_{nmt} – Quantity of raw material ‘n’ received by manufacturer ‘m’ in period ‘t’

E_{dt} – Quantity of finished product received by distributor ‘d’ in period ‘t’

F_{rt} – Quantity of finished product received by retailer ‘r’ in period ‘t’

Q_{mt} – Total quantity of finished product to start producing at time period ‘t’ (This will be ready for shipping after production lead time of LT_m)

MI_{nmt} – Inventory of raw material ‘n’ at manufacturer ‘m’ at the end of period ‘t’

DI_{dt} – Inventory of finished product at distributor ‘d’ at the end of period ‘t’

BO_{rt} – Cumulative backorders at the retailer ‘r’ at the end of period ‘t’

$NCAIR\_SM_{smt}$ – No. of containers through air, sent from supplier ‘s’ to manufacturer ‘m’, in time period ‘t’ (This will reach manufacturer ‘m’ after A_{1sm} time periods)

$NCAIR\_MD_{mdt}$ – No. of containers through air, sent from manufacturer ‘m’ to distributor ‘d’, in time period ‘t’ (This will reach distributor ‘d’ after B_{1md} time periods)

$NCAIR\_DR_{drt}$ – No. of containers through air, sent from distributor ‘d’ to retailer ‘r’, in time period ‘t’ (This will reach retailer ‘r’ after C_{1dr} time periods)

$NCROAD\_SM_{smt}$ – No. of containers through road, sent from supplier ‘s’ to manufacturer ‘m’, in time period ‘t’

$NCROAD\_MD_{mdt}$ – No. of containers through road, sent from manufacturer ‘m’ to distributor ‘d’, in time period ‘t’

$NCROAD\_DR_{drt}$ – No. of containers through road, sent from distributor ‘d’ to retailer ‘r’, in time period ‘t’

$NCRAIL\_SM_{smt}$ – No. of containers through rail, sent from supplier ‘s’ to manufacturer ‘m’, in time period ‘t’

$NCRAIL\_MD_{mdt}$ – No. of containers through rail, sent from manufacturer ‘m’ to distributor ‘d’, in time period ‘t’

$NCRAIL\_DR_{drt}$ – No. of containers through rail, sent from distributor ‘d’ to retailer ‘r’, in time period ‘t’

$NCOCEAN\_SM_{smt}$ – No. of containers through ocean, sent from supplier ‘s’ to manufacturer ‘m’, in time period ‘t’

$NCOCEAN\_MD_{mdt}$ – No. of containers through ocean, sent from manufacturer ‘m’ to distributor ‘d’, in time period ‘t’

$NCOCEAN\_DR_{drt}$ – No. of containers through ocean, sent from distributor ‘d’ to retailer ‘r’, in time period ‘t’ (This will reach retailer ‘r’ after C_{4dr} time periods)

3.2.5 Objective function

Objective 1: Profit is given by difference between revenue from sales and the total costs incurred (sum of raw material procurement, transportation, production and inventory holding costs).

$$
\begin{aligned}
&Maximize\ Profit\ Z_1 \\
&\quad = Revenue\ from\ sales - [Raw\ material\ procurement\ cost + Production\ cost \\
&\quad + Transportation\ cost + Inventory\ holding\ cost\ at\ the\ distributor \\
&\quad + Inventory\ holding\ cost\ at\ the\ manufacturer]
\end{aligned}
$$

$$Revenue\ from\ sales = SP \times \sum_{r=1}^{R} \sum_{t=1}^{T} F_{rt}$$

$$Raw\ materrial\ procurement\ cost = \sum_{n=1}^{N}\sum_{t=1}^{T}\sum_{i=1}^{4}\sum_{s=1}^{S}\sum_{m=1}^{M}(RMC_{ns} \times X_{nsmit})$$

$$Production\ cost = PC \times \sum_{m=1}^{M}\sum_{t=1}^{T} Q_{mt}$$

$$Inventory\ holding\ cost\ at\ the\ distributors = \sum_{d=1}^{D}\sum_{t=1}^{T}(DI_{dt} \times DIC_{d})$$

$$Inventory\ holding\ cost\ at\ the\ manufacturers\ for\ the\ raw\ materials$$

$$= \sum_{t=1}^{T}\sum_{m=1}^{M}\sum_{n=1}^{N}(MI_{nmt} \times MIC_{nm})$$

(Note: No inventory of finished goods at manufacturers)

$Container\ transportation\ cost$

$$= CRAIL \times (\sum_{s=1}^{S}\sum_{m=1}^{M}\sum_{t=1}^{T} NCRAIL\_SM_{smt} + \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{t=1}^{T} NCRAIL\_MD_{mdt} + \sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{t=1}^{T} NCRAIL\_DR_{drt}) + COCEAN \times (\sum_{s=1}^{S}\sum_{m=1}^{M}\sum_{t=1}^{T} NCOCEAN\_SM_{smt} + \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{t=1}^{T} NCOCEAN\_MD_{mdt} + \sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{t=1}^{T} NCOCEAN\_DR_{drt}) + CROAD \times (\sum_{s=1}^{S}\sum_{m=1}^{M}\sum_{t=1}^{T} NCROAD\_SM_{smt} + \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{t=1}^{T} NCROAD\_MD_{mdt} + \sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{t=1}^{T} NCROAD\_DR_{drt}) + CAIR \times (\sum_{s=1}^{S}\sum_{m=1}^{M}\sum_{t=1}^{T} NCAIR\_SM_{smt} + \sum_{m=1}^{M}\sum_{d=1}^{D}\sum_{t=1}^{T} NCAIR\_MD_{mdt} + \sum_{d=1}^{D}\sum_{r=1}^{R}\sum_{t=1}^{T} NCAIR\_DT_{drt})$$

Objective 2: In this thesis, we use quantity of backorder to represent customer responsiveness, so we want to minimize the total backorders at the retailers:

$$Minimize\ total\ backorders = Z_2 = \sum_{t=1}^{T}\sum_{r=1}^{R} BO_{rt}$$

Objective 3: Minimize total risk at the suppliers, manufacturers, distributors and transportation links. It is equivalent to the sum of the product of the disruption risk indices and the number of units passing through the corresponding nodes or links.

$$Minimize\ total\ risk = Z_3$$

$$= \sum_{t=1}^{T} \Big\{ \sum_{s=1}^{S} (RS_{st} \times \sum_{i=1}^{4} \sum_{m=1}^{M} \sum_{n=1}^{N} X_{nsmit})$$

$$+ \sum_{m=1}^{M} (RM_{mt} \times \sum_{i=1}^{4} \sum_{d=1}^{D} Y_{mdit}) + \sum_{d=1}^{D} (RD_{dt}$$

$$\times \sum_{i=1}^{4} \sum_{r=1}^{R} Z_{drit}) + \sum_{i=1}^{4} \sum_{s=1}^{S} \sum_{m=1}^{M} (RTSM_{smit} \times \sum_{n=1}^{N} X_{nsmit})$$

$$+ \sum_{i=1}^{4} \sum_{m=1}^{M} \sum_{d=1}^{D} (RTMD_{mdit} \times Y_{mdit}) + \sum_{i=1}^{4} \sum_{d=1}^{D} \sum_{r=1}^{R} (RTDR_{drit} \times Z_{drit}) \Big\}$$

3.2.6 Constraints:

1. <u>Constraints at the Manufacturers</u>

- Total quantity of raw material ‘n’ received by manufacturer ‘m’ in period ‘t’:

$$D_{nmt} = \sum_{s=1}^{S} [X_{nsm1(t-A_{1sm})} + X_{nsm2(t-A_{2sm})} + X_{nsm3(t-A_{3sm})} + X_{nsm4(t-A_{4sm})}], \forall n, m, t \quad (3.1)$$

- Raw material inventory balance:

$$MI_{nm(t-1)} + D_{nmt} = a_n \times Q_{mt} + MI_{nmt}, \forall n, m, t > 1 \quad (3.2)$$

- All the raw materials occupy the same amount of space, and could not exceed manufacturer’s raw material storage capacity:

$$\sum_{n=1}^{N} MI_{nmt} \leq MCAP_m,\ \forall m, t \quad (3.3)$$

- Manufacturer’s production capacity:

$$Q_{mt} \leq PMCAP_m, \forall m, t \quad (3.4)$$

- Total quantity of finished product starting at time ‘t’ and available for shipping:

$$\sum_{d=1}^{D}\sum_{i=1}^{4} Y_{mdit} = Q_{m(t+LT_m)}, \forall m, t \quad (3.5)$$

- Capacity of link from supplier to manufacturer:

$$NCAIR\_SM_{smt} \leq SMMAX_{1sm}, \forall s, m, t \quad (3.6)$$

$$NCRAIL\_SM_{smt} \leq SMMAX_{2sm}, \forall s, m, t \quad (3.7)$$

$$NCROAD\_SM_{smt} \leq SMMAX_{3sm}, \forall s, m, t \quad (3.8)$$

$$NCOCEAN\_SM_{smt} \leq SMMAX_{4sm}, \forall s, m, t \quad (3.9)$$

- Balance between number of containers from supplier to manufacturer and quantity of shipped raw material:

$$\sum_{n=1}^{N} X_{nsm1t} \leq NCAIR\_SM_{smt} \times CPAIR, \forall s, m, t \quad (3.10)$$

$$\sum_{n=1}^{N} X_{nsm2t} \leq NCRAIL_{SM\,smt} \times CPRAIL, \forall s, m, t \quad (3.11)$$

$$\sum_{n=1}^{N} X_{nsm3t} \leq NCROAD\_SM_{smt} \times CPROAD, \forall s, m, t \quad (3.12)$$

$$\sum_{n=1}^{N} X_{nsm4t} \leq NCOCEAN\_SM_{smt} \times CPOCEAN, \forall s, m, t \quad (3.13)$$

2. <u>Constraints at the Distributors</u>

- Total quantity of finished product received by distributor ‘d’ in period ‘t’:

$$E_{dt} = \sum_{m=1}^{M} [Y_{md1(t-B_{1md})} + Y_{md2(t-B_{2md})} + Y_{md3(t-B_{3md})} + Y_{md4(t-B_{4md})}, \forall d, t \quad (3.14)$$

- Finished product inventory balance:

$$DI_{d(t-1)} + E_{dt} = DI_{dt} + \sum_{r=1}^{R}\sum_{i=1}^{4} Z_{drit}, \forall d, r, t \quad (3.15)$$

- Distributor finished product storage capacity:

$$DI_{dt} \leq DCAP_d, \forall d, t \quad (3.16)$$

- Capacity of link from manufacturer to distributor:

$$NCAIR\_MD_{mdt} \leq MDMAX_{1md}, \forall m, d, t \tag{3.17}$$

$$NCRAIL\_MD_{mdt} \leq MDMAX_{2md}, \forall m, d, t \tag{3.18}$$

$$NCROAD\_MD_{mdt} \leq MDMAX_{3md}, \forall m, d, t \tag{3.19}$$

$$NCOCEAN\_MD_{mdt} \leq MDMAX_{4md}, \forall m, d, t \tag{3.20}$$

- Balance between number of containers from manufacturer to distributor and quantity of shipped finished product:

$$Y_{md1t} \leq NCAIR\_MD_{mdt} \times CPAIR, \forall m, d, t \tag{3.21}$$

$$Y_{md2t} \leq NCRAIL\_MD_{mdt} \times CPRAIL, \forall m, d, t \tag{3.22}$$

$$Y_{md3t} \leq NCROAD\_MD_{mdt} \times CPROAD, \forall m, d, t \tag{3.23}$$

$$Y_{md4t} \leq NCOCEAN\_MD_{mdt} \times CPOCEAN, \forall m, d, t \tag{3.24}$$

3. <u>Constraints at the Retailers</u>

- Total quantity of finished product received by retailer ‘r’ in period ‘t’:

$$F_{rt} = \sum_{d=1}^{D} [Z_{dr1(t-C_{1dr})} + Z_{dr2(t-C_{2dr})} + Z_{dr3(t-C_{3dr})} + Z_{dr4(t-C_{4dr})}, \forall r, t \tag{3.25}$$

- Cumulative backorder at retailer ‘r’ at the end of period ‘t’:

$$DEM_{rt} - F_{rt} + BO_{r(t-1)} = BO_{rt}, \forall r, t \tag{3.26}$$

- Capacity of link from distributor to retailer:

$$NCAIR\_DR_{drt} \leq DRMAX_{1dr}, \forall d, r, t \tag{3.27}$$

$$NCRAIL\_DR_{drt} \leq DRMAX_{2dr}, \forall d, r, t \tag{3.28}$$

$$NCROAD\_DR_{drt} \leq DRMAX_{3dr}, \forall d, r, t \tag{3.29}$$

$$NCOCEAN\_DR_{drt} \leq DRMAX_{4dr}, \forall d, r, t \tag{3.30}$$

- Balance between number of containers from distributor to retailer and quantity of shipped finished product:

$$Y_{dr1t} \leq NCAIR\_DR_{drt} \times CPAIR, \forall d, r, t \quad (3.31)$$

$$Y_{dr2t} \leq NCRAIL\_DR_{drt} \times CPRAIL, \forall d, r, t \quad (3.32)$$

$$Y_{dr3t} \leq NCROAD\_DR_{drt} \times CPROAD, \forall d, r, t \quad (3.33)$$

$$Y_{dr4t} \leq NCOCEAN\_DR_{drt} \times CPOCEAN, \forall d, r, t \quad (3.34)$$

- Other constraints on the variables:

X_{nsmit}, Y_{mdit}, Z_{drit}, D_{nmt}, E_{dt}, F_{rt}, Q_{mt}, MI_{nmt}, DI_{dt}, BO_{rt} are non-negative numbers

$NCAIR\_SM_{smt}$, $NCAIR\_MD_{mdt}$, $NCAIR\_DR_{drt}$, $NCROAD\_SM_{smt}$, $NCROAD\_MD_{mdt}$, $NCROAD\_DR_{drt}$, $NCRAIL\_SM_{smt}$, $NCRAIL\_MD_{mdt}$, $NCRAIL\_DR_{drt}$, $NCOCEAN\_SM_{smt}$, $NCOCEAN\_MD_{mdt}$, $NCOCEAN\_DR_{drt}$ are non-negative numbers and integers (3.35)

3.3 Goal Programming Solutions (Ravindran and Warsing (2013), Masud and Ravindran (2008, 2009))

The supply chain network model developed in section 3.2 is a multi-criteria mixed integer linear programming problem. We apply the Goal Programming approach to solve the problem. Goal programming (GP) requires the decision maker to set target levels for the objectives and specify the relative importance of achieving the target. These target values are treated as goal constraints that the decision maker desires to achieve. These targets may or maybe not be achievable. This approach attempts to find an optimal solution that comes as close to the targets as possible. Hence the objective function in GP is to minimize the deviations from the targets. Masud and Ravindran (2008) present four types of GP formulations: (1) Preemptive Goal Programming (PGP)

(2) Non-preemptive Goal Programming (NP-GP)

(3) Minmax Goal Programming

(4) Fuzzy Goal Programming

In this thesis, we apply PGP and NPGP, which are explained below.

3.3.1 Preemptive Goal Programming

Decision maker needs to rank the objective functions and the method considers low priority goals only after achieving the high priority goals. The preemptive method uses ordinal ranking or preemptive priorities. The following is the PGP formulation for the three criteria problem presented in section 3.2:

$$\text{Min Z} = P_1(d_1^-) + P_2(d_2^+) + P_3(d_3^+) \tag{3.36}$$

Subject to:

$$Z_1 - d_1^+ + d_1^- = target\ 1 \quad \text{(Profit)}$$

$$Z_2 - d_2^+ + d_2^- = target\ 2 \quad \text{(Backorder)}$$

$$Z_3 - d_3^+ + d_3^- = target\ 3 \quad \text{(Risk)}$$

$$d_i^-, d_i^+ \geq 0 \quad i = 1,2,3$$

Constraints (3.1) – (3.35)

$$d_i^+ - Positive\ deviation\ from\ target\ value\ of\ objective\ i$$

$$d_i^- - Negative\ deviation\ from\ target\ value\ of\ objective\ i$$

Recall that P1 represents maximizing the profit, P2 represents minimizing the backorder and P3 represents minimizing the risk index. For illustration, we assume that P1 is more important than P2 and P2 is more important than P3. Priorities can be reversed to see the impact on the solution also. The deviation variables $d_1^-\ and\ d_1^+$ represent the underachievement and overachievement of the first target. For maximizing the first objective, the underachievement is to be minimized, which is equivalent to maximize the profit. Hence, we use d_1^- in the objective function (3.36). For minimizing the second objective, the overachievement is to be maximized because we want to minimize the backorder. Target 2 may or may not be achievable, and d_2^+ represents the amount of backorders over the specified target. Hence, d_2^+ is minimized in equation (3.36). For the third objective, minimizing the overachievement d_3^+ is equivalent to minimizing the risk index.

3.3.2 Non-preemptive Goal Programming

In NPGP, the decision maker need to specify weight for each objective. Once the set of weights are specified, the goal programming reduces to a single objective problem. The cardinal weights could be obtained using methods such as Rating method, Borda Count and AHP. The following is NPGP formulation:

$$\text{Min Z} = W_1(d_1^-) + W_2(d_2^+) + W_3(d_3^+)$$

Subject to:

$$Z_1 - d_1^+ + d_1^- = target\ 1 \quad \text{(Profit)}$$

$$Z_2 - d_2^+ + d_2^- = target\ 2 \quad \text{(Backorder)}$$

$$Z_3 - d_3^+ + d_3^- = target\ 3 \quad \text{(Risk)}$$

$$W_1 + W_2 + W_3 = 1$$

$$d_i^-, d_i^+ \geq 0 \quad i = 1,2,3$$

$$W_1, W_2, W_3 \geq 0$$

Constraints (3.1) – (3.35)

$$d_i^+ - Positive\ deviation\ from\ target\ value\ of\ objective\ i$$

$$d_i^- - Negative\ deviation\ from\ target\ value\ of\ objective\ i$$

This model needs to be scaled due to the use of the weights. The weights W_1, W_2, W_3 represent the trade-off made by decision makers. Once the assignment of weights is specified, the goal programming in section 3.2 reduces to a single objective optimization problem.

3.3.3 Comparison of PGP and NPGP

Pros and cons of the preemptive and the non-preemptive GP methods are given in Table 3.1.

Table 3.1 Pros and Cons of Two GP Formulations

	Preemptive GP	Non-preemptive GP
Pros	Do not need scaling	Trade-offs among objectives are allowed, just need to change the set of weights
	Easier to get preemptive priorities	It is easier to solve because this problem only has one objective
Cons	Do not allow trade-off among the objectives	Need scaling of the objectives
	It is more difficult and time-consuming compared to solve a sequential optimization problem by priority	Weights are not easy to obtain

3.4 Supply Chain Network Vulnerability Analysis

In this thesis, we use Resiliency Enhancement Analysis via Deletion and Insertion (READI) method of Harrison et al. (2013) to improve the supply chain resiliency. READI not only examines the impact of the removal and insertion of various supply chain nodes, but also is flexible for assessing the impact of critical supply chain infrastructure of any kind – transportation lanes, manufacturing capabilities, services, and others. READI method has been applied to several disruption scenarios for a manufacturer and distributor of consumer packaged goods firm in North America, consisting of 5 supply points, 4 plants, and 13 distribution centers.

READI optimizes various configurations of the supply chain network in a structured fashion. First, a baseline optimization model is solved. Then a single node is removed from the supply chain network and re-optimize after is done on the modified network. This step allows for an assessment of the impact of the removed node. The disaster duration is classified as short-term or long-term. To investigate shorter-term resiliency for each possible disruption, READI re-optimizes product flows and also allows new DCs to be brought online. These are two different reconfiguration options, the first one is the most restrictive, but it also can be implemented the fastest in response to a disruption since a realignment of product flows is typically less time-consuming than acquiring additional DC capabilities. The second option facilitates the identification of appropriate backup distribution locations. To address longer-term disruptions, READI re-optimizes product flows, permits both addition of new DCs and close existing ones. Then IT investigateS the resiliency obtained by greater production flexibility. Note that the assumption here is that all plants are capable of making all products, so that the impacts of disruptions on the current network could be compared. In summary, there are four scenarios of each facility. For all scenarios, this paper seeks to minimize total cost of production, distribution, and transportation subject to meeting predetermined customer demands. From the numerical results, we see that when disruption happens, the percentage of missed demand of each facility and cost change when no demand is missed, and so we could know that whether this mitigation strategy is worthy or not.

3.4.1 Supply Chain Network Vulnerability Analysis Framework

In this thesis, we apply the principle of READI to evaluate the vulnerability and improve the resiliency of the supply chain network. Our approach is summarized below:

Step1: Solve a baseline optimization model, which is the mathematical model developed in section 3.2 by Preemptive Goal Programming and Non-preemptive Goal Programming methods.

Step2: Remove a single node or link from the baseline supply chain network. For example, if manufacturer 1 is disrupted in week 5, we set the quantity of finished product in week 5 at this manufacturer as 0 and the quantity of finished product shipped from this manufacturer in period 5 as 0 also.

Step3: Generate several disruption scenarios, re-optimize the supply chain network and assess the impact of the removed node or link on all three objectives. We consider the change in each objective as the impact of disruption. For example, when supplier 1 is disrupted, the effect of disruption may cause the profit to reduce by 10%. The total number of scenarios is equal to the number of chosen facilities and transportation links, and the disruptions in node or link are different, which are dependent on specific situations.

Step4: Apply mitigation strategies and then re-optimize the supply chain network. For each scenario, we set a corresponding mitigation strategy. Then we add this condition into supply chain network and re-optimize it to see whether this strategy is worthy or not. We consider the changes to each objective as the effectiveness of the mitigation strategy. For example, after applying a backup supplier, the responsiveness objective may improve by 5% and the profit objective may decrease by 6%, compared to the baseline optimal solution.

Step5: Analyze the mitigation strategy cost versus resiliency benefit. For example, with a backup supplier, the purchasing cost of raw materials may be higher than that of original supplier. Hence, additional cost may be incurred. However, the net profit may still be higher compared to no mitigation strategy.

3.4.2 Analysis of Disruptions

We assume that only one type of disruption occurs in each node or link. Based on the current supply chain network, we analyze the specific potential risk of each facility and each transportation link, then we could generate several disruption scenarios. For each facility or link, there exists a scenario. We could choose some of them or all of them to analyze. After analyzing, the critical nodes and links are known, and it is clear that some nodes and links cause greater negative effect during disruption.

3.5 Risk Mitigation Analysis

After we know the degree of resiliency of the supply chain network when facing disruptions, we could incorporate risk mitigation strategies, such as a backup facility and extra inventory, to illustrate how the resiliency can be improved for the supply chain network.

Chapter 4

Illustrative Example

In this chapter, an example is presented to illustrate the multi-criteria model developed in Chapter 3. The following input data come from Rahavan's thesis (2013). The example problem is solved using Goal Programming methods (preemptive and non-preemptive).

4.1 Input Data

Consider the supply chain network described in Chapter 3, there are four stages – Supplier, Manufacturer, Distributor and retailer. The stages are connected with one another by means of four modes of transportation – Air, Road, Rail and Ocean. In this example, the time unit is week and the planning horizon is set at 15 weeks. We illustrate the multi-criteria model with the network parameters listed in Table 4.1.

Table 4.1 Supply Chain Network Parameters

Notation	Description	Value
S	No. of suppliers	4
M	No. of manufacturers	2
D	No. of distributors	3
R	No. of retailers	7

The cost components that are involved in calculating the profit objective, namely, the selling price/unit, the production cost/unit, and the inventory holding costs are presented in Table 4.2.

Table 4.2 Cost Components in USD

Notation	Description	Cost
SP	Selling price of one unit of finished product	$240
PC	Cost of producing one unit of finished product	$25
MIC	Inventory holding cost at manufacturer location	$0.5/unit/week
DIC	Inventory holding cost at distributor location	$0.5/unit/week

We assume that two different types of raw materials (n=1, 2) are required to build the finished product. One unit of raw material 1 and two units of raw material 2 go into producing one unit of the finished product. Here we assume that all the four suppliers can supply both raw materials. The cost of procuring the raw materials from the different suppliers are given in Table 4.3.

Table 4.3 Raw Material Cost (RMC_{ns}) at the Suppliers in USD/unit

Supplier	Raw material 1	Raw material 2
S1	40.66	14.91
S2	36.83	37.60
S3	37.84	43.83
S4	38.08	41.66

The production lead time at the manufacturing units is assumed to be two weeks. We assume that both raw materials and the finished product require the same amount of storage space. The Manufacturers' capacity to hold inventory of raw material and production capacities are presented in Table 4.4. The boundary conditions related to the initial and final inventory of raw materials at the manufacturing plants are given in Table 4.5.

Table 4.4 Inventory Capacity ($MCAP_m$) and Production Capacity ($PMCAP_m$) of Manufacturers

Manufacturer	Inventory capacity (units)	Production capacity (units)
M1	2841	1077
M2	2418	1162

Table 4.5 Initial and Ending Inventory of Raw Material for Manufacturers in units

Manufacturer	Initial inventory (MII_{nm})	Ending inventory (MEI_{nm})
M1	500 for n=1	100
	1000 for n=2	100
M2	500 for n=1	100
	1000 for n=2	100

The capacity of the DC to hold finished product inventory is listed in Table 4.6. The boundary conditions relating to the initial and ending inventory at the DCs are listed in Table 4.7.

Table 4.6 Capacity of DC to Hold Finished Product ($DCAP_d$) in units

Distributor	Inventory capacity
D1	791
D2	800
D3	816

Table 4.7 Initial and Ending Inventory of Finished Product for DC

Distributor	Initial inventory (DII_d)	Ending inventory (DEI_d)
D1	750	50
D2	750	50
D3	750	50

Table 4.8 gives the forecasted demand at the retailers for the next fifteen weeks. It is to be noted that these values can be updated as and when they change, and the model can be re-run with the updated values to capture the effect of changing forecasts.

Table 4.8 Forecasted Demand (DEM_{rt}) at the Retailers in number of units by week

Week	R1	R2	R3	R4	R5	R6	R7
1	166	201	207	245	233	195	195
2	239	237	249	154	158	206	207
3	171	210	243	208	219	172	172
4	153	202	216	167	204	189	182
5	220	241	191	243	193	230	190
6	150	229	234	191	227	157	164
7	157	184	166	242	208	227	154
8	193	203	158	215	157	164	175
9	157	227	180	194	186	194	170
10	192	240	174	160	218	217	192
11	152	154	184	200	205	244	160
12	167	240	189	181	205	242	216
13	241	161	242	186	192	245	177
14	174	186	228	247	216	176	150
15	153	185	174	177	152	238	156

The transportation capacities are at 1000 units for all modes of transportation, between all stages, in all time periods (Table 4.9). The lead time is assumed to be one week if shipped using air, two weeks if shipped by road, three weeks if shipped by rail and four weeks if shipped using ocean between all stages in all the time periods (Table 4.10).

Table 4.9 Transportation Capacities (units)

	Air (i=1) (unit)	Road (i=2) (unit)	Rail (i=3) (unit)	Ocean (i=4) (unit)
Supplier to Manufacturer ($SMMAX_{ism}$)	1000	1000	1000	1000
Manufacturer to Distributor ($MDMAX_{imd}$)	1000	1000	1000	1000
Distributor to Retailer ($DRMAX_{idr}$)	1000	1000	1000	1000

Table 4.10 Transportation Lead Time for the Four Modes of Transportation (weeks)

	Air (i=1)	Road (i=2)	Rail (i=3)	Ocean (i=4)
Supplier to Manufacturer	1	2	3	4
Manufacturer to Distributor	1	2	3	4
Distributor to Retailer	1	2	3	4

Transportation costs for the four modes per container are set by transportation companies and are given in Table 4.11. Quantity of raw material or finished product per container are given in Table 4.12.

Table 4.11 Transportation Costs for Four Modes

Description	Notation	Cost in USD
Cost of shipping one container through air	CAIR	$2000
Cost of shipping one container through road	CROAD	$1820
Cost of shipping one container through rail	CRAIL	$1680
Cost of shipping one container through ocean	COCEAN	$1500

Table 4.12 Container Capacities for Shipments through Four Transportation Modes

Description	Notation	Capacity (units)
Capacity of a container for air	CPAIR	100
Capacity of a container for rail	CPRAIL	100
Capacity of a container for road	CPROAD	100
Capacity of a container for ocean	CPOCEAN	100

The risk indices for the different nodes and links are computed using one or more of the methods, such as Rating Method, Ranking Method, Pair-wise comparison using Borda Count and AHP method. Rahavan uses the AHP method to calculate all nodes risk indices, the Rating method to get link risk indices for ocean, the Pair-wise comparison using Borda Count to get link risk indices for Road and Borda Count method to get link risk indices for Air. All results have been scaled. The scaling is from 1 to 10, where 10 is the riskiest and 1 is the least risky. For example, the disruption risk index for manufacturer 1 is 2.641 and that for manufacturer 2 is 1.016, which means that manufacturer 1 has higher chances of causing disruption in the supply chain than manufacturer 2. In addition, according to the historical records, manufacturer 1 had several strikes and manufacturer 2 suffered three hurricanes, and the frequency of strikes in manufacturer 1 was higher, while hurricanes were rare. So the risk indices of manufacturer 1 is higher. For the sake of brevity, the calculations are not repeated for every node and link. Only the final values are presented in Tables 4.13 and 4.14. Similar to the forecasted retailer demands, the risk indices can also be changed any time during the planning horizon. The model can be re-run using the updated risk indices to capture the effect of the changing indices on the inventory and transportation policies for the forthcoming time periods. This approach is known as the rolling horizon implementation of the model. In this example, it is assumed that the risk indices remain constant over the planning horizon for all nodes and links in the network.

Table 4.13 Facility Risk Indices

Facility	**Risk Index**
Supplier 1	4.494
Supplier 2	8.636
Supplier 3	4.357
Supplier 4	3.690
Manufacturer 1	2.641
Manufacturer 2	1.016
Distributor 1	7.607
Distributor 2	4.535
Distributor 3	2.955

Table 4.14 Link/Transportation Risk Indices

	Air	Road	Rail	Ocean
S1-M1	5.989	8.247	9.559	1.625
S1-M2	7.837	1.653	2.057	2.768
S2-M1	4.210	7.886	1.845	2.869
S2-M2	6.299	1.713	4.185	6.121
S3-M1	9.428	6.722	3.338	1.974
S3-M2	8.476	3.041	5.914	7.195
S4-M1	3.775	1.285	1.282	9.701
S4-M2	6.229	7.470	3.219	5.021
M1-DC1	9.592	6.405	9.287	3.889
M1-DC2	5.324	6.722	5.066	3.341
M1-DC3	4.589	6.145	6.746	8.462
M2-DC1	5.546	3.047	8.458	4.418
M2-DC2	5.305	2.904	9.287	1.393
M2-DC3	8.351	6.354	8.663	9.503
DC1-R1	7.378	6.746	8.828	7.748
DC1-R2	5.425	2.045	3.299	7.478
DC1-R3	5.166	8.616	8.535	1.898
DC1-R4	5.223	4.297	9.217	9.227
DC1-R5	7.302	5.670	2.910	6.765
DC1-R6	3.408	3.756	9.678	6.778
DC1-R7	3.930	4.266	9.087	8.659
DC2-R1	4.689	2.895	4.553	9.048
DC2-R2	5.771	2.286	2.313	8.879
DC2-R3	7.639	7.552	2.835	2.149
DC2-R4	1.839	2.447	3.811	7.736
DC2-R5	4.221	6.975	5.302	2.987
DC2-R6	1.923	2.089	1.078	2.841
DC2-R7	8.347	9.471	9.392	1.055
DC3-R1	6.421	4.189	9.185	9.786
DC3-R2	3.084	3.350	9.513	8.626
DC3-R3	4.048	2.242	5.116	8.006
DC3-R4	3.740	6.284	4.525	3.163
DC3-R5	9.806	3.924	1.904	3.956
DC3-R6	2.503	6.128	3.252	5.616
DC3-R7	5.589	1.147	5.763	1.546

4.2 Ideal Values, Bounds and Targets

The optimization problem has a total of 5143 variables and 5616 constraints. The problem was solved in LINGO 11. For problems that had feasible solutions, optimum was reached at an average of 2 seconds. To get the ideal values, we get the optimal solutions from three single-objective optimization problems. Ideal values are the best values for each objective ignoring other objectives. Every time we only consider one objective, and could get other two objectives' values. So these nine values could consist of a 3×3 matrix in which rows are values of profit or backorders or risk and columns are max profit, min backorder and min risk solutions. From the profit row, we choose the highest value as the upper bound of profit and the smallest value as the lower bound of profit. From the backorder row, we choose the smallest value as the lower bound of backorder and from the risk column we choose the lower bound as the ideal value. Then we set the targets for each objective function, which are the upper bound of profit, lower bound of backorder and lower bound of risk. The ideal solution is (1670399, 37011, 175665), which is unachievable. The bounds, ideal values and targets are presented in Table 4.15. For illustrative purposes, the targets have been set at the ideal values.

Table 4.15 Bounds, Ideal Values and Targets for the Objectives

Objectives	Lower Bound	Upper Bound	Ideal Value	Target
Max profit	1191765	1670399	1670399	1670399
Min backorder	37011	84236	37011	37011
Min risk	175665	1177804	175665	175665

Since the total demand is 163691, the ideal value of backorder (37011) means that the unmet demand is about 23% due to insufficient production or inventory capacities.

4.3 Formulation of PGP and NPGP

4.3.1 PGP formulation

In our model, it is assumed that the decision maker ranks the priorities (from high to low) as P1: profit, P2: backorder, P3: risk. Hence, the objective function for the Goal Programming model is to minimize the deviations from the target values defined for each objective. The preemptive goal programming formulation would be:

$$\text{Min Z} = P_1(d_1^-) + P_2(d_2^+) + P_3(d_3^+)$$

Subject to:

$$CRAIL \times (\sum_{s=1}^{4}\sum_{m=1}^{2}\sum_{t=1}^{15} NCRAIL_{SM_{smt}} + \sum_{m=1}^{2}\sum_{d=1}^{3}\sum_{t=1}^{15} NCRAIL_{MD_{mdt}} + \sum_{d=1}^{3}\sum_{r=1}^{7}\sum_{t=1}^{15} NCRAIL_{DR_{drt}})$$
$$+ COCEAN \times$$
$$\times (\sum_{s=1}^{4}\sum_{m=1}^{2}\sum_{t=1}^{15} NCOCEAN_{SM_{smt}} + \sum_{m=1}^{2}\sum_{d=1}^{3}\sum_{t=1}^{15} NCOCEAN_{MD_{mdt}}$$
$$+ \sum_{d=1}^{3}\sum_{r=1}^{7}\sum_{t=1}^{15} NCOCEAN_{DR_{drt}}) + CROAD$$
$$\times (\sum_{s=1}^{4}\sum_{m=1}^{2}\sum_{t=1}^{15} NCROAD_{SM_{smt}} + \sum_{m=1}^{2}\sum_{d=1}^{3}\sum_{t=1}^{15} NCROAD_{MD_{mdt}}$$
$$+ \sum_{d=1}^{3}\sum_{r=1}^{7}\sum_{t=1}^{15} NCROAD_{DR_{drt}}) + CAIR$$
$$\times (\sum_{s=1}^{4}\sum_{m=1}^{2}\sum_{t=1}^{15} NCAIR_{SM_{smt}} + \sum_{m=1}^{2}\sum_{d=1}^{3}\sum_{t=1}^{15} NCAIR_{MD_{mdt}} + \sum_{d=1}^{3}\sum_{r=1}^{7}\sum_{t=1}^{15} NCAIR_{DT_{drt}})$$
$$- d_1^+ + d_1^- = target\ 1\ (profit) \tag{4.1}$$

$$\sum_{t=1}^{15}\sum_{r=1}^{7} BO_{rt} - d_2^+ + d_2^- = target2\ (backorder) \tag{4.2}$$

$$\sum_{t=1}^{15}\Big\{ \sum_{s=1}^{4}(RS_{st} \times \sum_{i=1}^{4}\sum_{m=1}^{2}\sum_{n=1}^{2} X_{nsmit})$$
$$+ \sum_{m=1}^{2}(RM_{mt} \times \sum_{i=1}^{4}\sum_{d=1}^{3} Y_{mdit}) + \sum_{d=1}^{3}(RD_{dt}$$
$$\times \sum_{i=1}^{4}\sum_{r=1}^{7} Z_{drit}) + \sum_{i=1}^{4}\sum_{s=1}^{4}\sum_{m=1}^{2}(RTSM_{smit} \times \sum_{n=1}^{2} X_{nsmit})$$
$$+ \sum_{i=1}^{4}\sum_{m=1}^{2}\sum_{d=1}^{3}(RTMD_{mdit} \times Y_{mdit})$$
$$+ \sum_{i=1}^{4}\sum_{d=1}^{3}\sum_{r=1}^{7}(RTDR_{drit} \times Z_{drit}) \Big\} - d_3^+ + d_3^- = target\ 3\ (risk) \tag{4.3}$$

$$d_i^-, d_i^+ \geq 0 \quad i = 1,2,3$$

Constraints (3.1) – (3.35) given in Chapter 3

$d_i^+ - Positive\ deviation\ from\ target\ value\ of\ objective\ i$

$d_i^- - Negative\ deviation\ from\ target\ value\ of\ objective\ i$

4.3.2 NPGP formulation

In our model, it is assumed that the decision maker sets about equal weights for the three objectives, which means that cardinal weight of profit objective is 0.34, that of backorder objective is 0.33, and that of risk objective is 0.33. The non-preemptive goal programming formulation would be:

$$\text{Min Z} = 0.34(d_1^-) + 0.33(d_2^+) + 0.33(d_3^+) \qquad (4.4)$$

Subject to: $Equations\ (4.1), (4.2)\ and\ (4.3)$

$$d_i^-, d_i^+ \geq 0 \quad i = 1,2,3$$

Constraints (3.1) – (3.35) given in Chapter 3

$$d_i^+ - Positive\ deviation\ from\ target\ value\ of\ objective\ i$$

$$d_i^- - Negative\ deviation\ from\ target\ value\ of\ objective\ i$$

Since the targets are set at ideal values, the objective functions given by equation (4.4), is equivalent to $Min\ Z = 0.34 \times Z1 + 0.33 \times Z2 + 0.33 \times Z3$ where Z1, Z2 and Z3 are the three objective functions.

4.4 Results of PGP and NPGP Problems

The result of the PGP problem are presented in Table 4.16 and the result of the NPGP problem are presented in Table 4.17. They represent the objective values that are achievable under “no disruption” scenario. We refer to them as the base model results. In addition, the unmet demand is about 41% of the total demand.

Table 4.16 Base Model Results of the PGP Problems

Preemptive priority	**Z_1**		**Z_2**		**Z_3**	
	Profit ($)	% deviation from target	Backorder（units）	% deviation from target	Risk	% deviation from target
P1>P2>P3	1670399	0%	67355	82%	211406	20%

Table 4.17 Base Model Results of the NPGP Problems

Non-preemptive weights	**Z_1**		**Z_2**		**Z_3**	
	Profit ($)	% deviation from target	Backorder (units)	% deviation from target	Risk	% deviation from target
(0.34,0.33,0.33)	1667146	4%	67705	83%	206324	17%

4.5 Analysis of Vulnerability under preemptive and non-preemptive method

In section 4.4, we have the base model results under no disruptions. Using the method mentioned in Chapter 3, we delete a node or link to introduce disruption and calculate the associated vulnerability. Also, we will compare short-term and long-term disruptions. We begin by generating some disruption scenarios.

4.5.1 Generating disruption scenarios

For illustrative purpose, we have generated 18 disruption scenarios, each represents a disruption at a facility or a transportation link.

- There are two scenarios for supplier disruptions, only two suppliers are chosen from the four suppliers.
- There are two scenarios for manufacturer disruptions.
- There are two scenarios for distributor disruptions, only two distributors are chosen from 3 distributors.
- There are twelve scenarios for transportation link disruptions, including 4 transportation links between suppliers and manufacturers, 4 transportation links between manufacturer and distributors, 4 transportation links between distributors and retailers.

For each disruption scenario, we also consider two disruption-durations (short-term and long-term) and two methods of model solution (preemptive and non-preemptive). In total, we solve $18 \times 2 \times 2 = 72$ optimization models for the vulnerability analysis.

For illustration, we assume that a disruption occurs in the beginning of a planning horizon, and the disruption-durations are 1 week and 2 week. For example, if a disruption occurs at week 1, then the disrupted facility or transportation link could resume its normal operation at weeks 2 or 3. We summarize the re-optimization process to the tactical model as follows:

Step1: Apply preemptive and non-preemptive methods to solve the optimization model, and get the raw material purchasing quantity, production quantity, distribution quantity, and inventory. (Base model results)

Step2: Reassign the decision variables corresponding to the disrupted facility or transportation link to zero during the disruption period. For example, if Supplier 1 is disrupted for short-term, then assign the variable representing the quantity of raw material shipped from supplier 1 to the manufacturers using mode 'i' in week 1 as zero. Recall that i = 1,2,3 and 4. If Supplier 1 is disrupted for long-term, then assign those decision variables for week 2 also as zero.

Step3: Re-optimize the model and compare the new supply chain network profit, backorder and risk with those from the base model in Step1. The difference represents the impact of the disruption.

4.5.2 Description of Scenarios

Scenario 1 and 2: The location of supplier 1 is prone to flood, and supplier 4 is prone to earthquake. When these natural disasters occur, the affected supplier cannot send any raw material during the disruption duration.

Scenario 3 and 4: In the past three years, manufacturer 1 had several strikes and manufacturer 2 suffered three hurricanes. So we consider these situations as potential disruptions. During the disruption duration, no product is produced by the disrupted manufacturer, and no finished products could be sent to the distribution centers.

Scenario 5 and 6: Distribution center 2 (DC 2) suffered a huge loss caused by fire two years ago, and for DC3, the quantity of finished products shipped to the retailers may be affected by restriction of import or export. Under these disruptions, we assume fire will destroy all inventory in DC 2, and the quantity of finished products sent by DC 3 will reduce by 70%.

Scenario 7, 8, 9 and 10: Four transportation links between supplier 1, supplier 4, manufacturer 1 and manufacturer 2 are affected by weather conditions. We analyze both short-term and long-term disruptions.

Scenario 11, 12, 13 and 14: Air transportation is not always available in four transportation links between manufacturer 1, manufacturer 2, DC 2 and DC 3.

Scenario 15, 16, 17 and 18: Road transportation in four transportation links between DC 2, DC 3, retailer 3 and retailer 4 are disturbed because of frequent strikes.

We list the possible disruptions in chosen suppliers, manufacturers, distribution centers and links in Table 4.18 and Table 4.19. We also specify that the corresponding decision variables to be set to zero during re-optimization. In all cases, we assume that only one type of disruption occurs at a given time.

Table 4.18 Disruption Scenario Description at Facilities

Scenario	**Node**	**Disruption**	**How to set variables in the model under short-term disruption**	**How to set variables in the model under long-term disruption**
1	Supplier 1	Flood	X_{n1mi1}=0 n=1,2; m=1,2; i=1,2,3,4	X_{n1mi1}=0, X_{n1mi2}=0 n=1,2; m=1,2; i=1,2,3,4
2	Supplier 4	Earthquake	X_{n4mi1}=0	X_{n4mi1}=0, X_{n4mi2}=0
3	Manufacturer 1	Labor issue/strike	Q_{11}=0, Y_{1di1}=0	Q_{11}=0, Q_{12}=0 Y_{1di1}=0, Y_{1di2}=0
4	Manufacturer 2	hurricane	Q_{21}=0, Y_{2di1}=0	Q_{21}=0, Q_{22}=0 Y_{2di1}=0, Y_{2di2}=0
5	DC 2	Fire	MI_{n21}=0, Z_{2ri1}=0	MI_{n21}=0, MI_{n22}=0 Z_{2ri1}=0, Z_{2ri2}=0
6	DC 3	Import/export restriction	Z_{21i1}=30% of Z_{21i1} in optimal model	Z_{21i1}=30% of Z_{21i1} in optimal model, Z_{21i2}=30% of Z_{21i2} in optimal model

Table 4.19 Disruption Scenario Description at Transportation Links

Scenario	Link	Disruption	How to set variables in model under short-term effect	How to set variables in model under long-term effect
7	Supplier 1 to manufacturer 1	Weather condition, so the quantity of raw material will reduce to 0	$X_{n11i1}=0$ n=1,2; i=1,2,3,4	$X_{n11i1}=0$, $X_{n11i2}=0$ n=1,2; i=1,2,3,4
8	Supplier 1 to manufacturer 2		$X_{n12i1}=0$	$X_{n12i1}=0$, $X_{n12i2}=0$
9	Supplier 4 to manufacturer 1		$X_{n41i1}=0$	$X_{n41i1}=0$, $X_{n41i2}=0$
10	Supplier 4 to manufacturer 2		$X_{n42i1}=0$	$X_{n42i1}=0$, $X_{n42i2}=0$
11	Manufacturer 1 to DC 2	Air transportation could not use during disruption duration	$Y_{1211}=0$	$Y_{1211}=0$, $Y_{1212}=0$
12	Manufacturer 1 to DC 3		$Y_{1311}=0$	$Y_{1311}=0$, $Y_{1312}=0$
13	Manufacturer 2 to DC 2		$Y_{2211}=0$	$Y_{2211}=0$, $Y_{2212}=0$
14	Manufacturer 2 to DC 3		$Y_{2311}=0$	$Y_{2311}=0$, $Y_{2312}=0$
15	DC 2 to retailer 3	Road transportation could not use during disruption duration	$Z_{2321}=0$	$Z_{2321}=0$, $Z_{2322}=0$
16	DC 2 to retailer 4		$Z_{2421}=0$	$Z_{2421}=0$, $Z_{2422}=0$
17	DC 3 to retailer 3		$Z_{3321}=0$	$Z_{3321}=0$, $Z_{3322}=0$
18	DC 3 to retailer 4		$Z_{3421}=0$	$Z_{3421}=0$, $Z_{3422}=0$

4.6 Impact of disruption

Using Tables 4.18 and 4.19, we re-optimize the goal programming model 18 times using PGP and 18 times using NPGP. Each time we just change the values of the corresponding variables to zero. We also compare two different disruption durations. In this illustration, we assume that the disruption occurs at week 1, the short-term disruption will last one week and the long-term disruption will last two weeks. It is easy to introduce disruptions at other weeks also. The total number of re-optimization should be $18 \times 4 = 72$. The impacts of disruptions are illustrated in Tables 4.20 – 4.23.

4.6.1 Impact of disruption under Preemptive Goal Programming

In this section, all 18 scenario re-optimization results are compared to the result of the base model solved by Preemptive Goal Programming, with priority P1>P2>P3. For each scenario, we get values of the three objectives after re-optimization, and calculate the difference from base model results. Then, the difference is divided by the base model result to get a percentage. These are given in Tables 4.20 and 4.21. The column Reduced Profit represents the impact of disruption on profit, and a smaller number is better. The last two columns represent the impacts of disruption on backorder and risk, and the smaller numbers are better.

Table 4.20 Impact of a Short-term Disruptions Compared to the Preemptive GP Base Model Results

Supply Chain component	Scenario	Disrupted Component	Reduced Profit	Increased Backorder	Increased Risk
Supplier	1	S1	4.1%	0.5%	42.9%
	2	S4	0%	0%	42.9%
Manufacturer	3	M1	3.0%	0.9%	29.5%
	4	M2	4.7%	1.5%	52.9%
DC	5	D2	7.0%	0%	64.0%
	6	D3	0%	0%	36.5%
Transportation links	7	S1-M1	0.3%	0%	31.1%
	8	S1-M2	0.1%	0%	42.0%
	9	S4-M1	0%	0%	35.7%
	10	S4-M2	0.5%	0%	34.3%
	11	M1-D2	0%	0%	31.9%
	12	M1-D3	0%	0%	31.9%
	13	M2-D2	0.3%	0.2%	32.0%
	14	M2-D3	0%	0%	31.9%
	15	D2-R3	0.4%	0%	32.2%
	16	D2-R4	0.8%	0%	32.2%
	17	D3-R3	0%	0%	32.3%
	18	D3-R4	0%	0%	32.0%

From Table 4.20, a short-term disruption will affect all facilities and links in terms of reduced profit, more backorder and more risk. We see that risk indices increase more, compared to other two objectives because its priority is the lowest in Preemptive GP. Disruption at Distributor 2 (scenario 5) causes the most impact in terms of reduced profit (7%) and increased risk (64%). Disruption at Manufacturer 2 (scenario 4) causes the most impact in terms of backorder (1.5%). In addition, there are some facilities and links that will not affect the profit and backorders, such as Supplier 4 (scenario 4) and DC3 (scenario 6), links (scenario 9, 11, 12, 14, 17, 18).

Table 4.21 presents the impact of long-term disruptions using the Preemptive GP model. The results show that the supply chain cannot reach the optimal conditions of the base model, when potential disruptions occur. In addition, disruptions at the facilities result in more negative impacts to the supply chain than the disruptions at the transportation links. Supplier S1, manufacturer M2 and distributor D2 are the top three facility disruptions causing higher backorders, profit reduction, and risk under long-term disruptions. Among all the transportation links, disruption at the link connecting D2 and R4 (scenario 16) results in higher negative impact to the supply chain in terms of profit, while disruptions at the links connecting M2 and D2 (scenario 13), S1 and M2 (scenario 8) result in higher negative impacts in terms of backorders and risk.

Table 4.21 Impact of Long-term Disruptions Compared to the Preemptive GP Base Model Results

Supply Chain component	Scenario	Disrupted Component	Reduced profit	Increased backorder	Increased risk
Supplier	1	S1	8.1%	0.5%	46.1%
	2	S4	0%	0%	48.8%
Manufacturer	3	M1	3.0%	0.9%	32.6%
	4	M2	4.8%	1.5%	45.8%
DC	5	D2	12.7%	0.5%	67.4%
	6	D3	0%	0%	40.9%
Transportation links	7	S1-M1	0.3%	0%	35.5%
	8	S1-M2	0.1%	0%	49.9%
	9	S4-M1	0%	0%	39.1%
	10	S4-M2	0.5%	0.5%	40.2%
	11	M1-D2	0%	0%	34.3%
	12	M1-D3	0%	0%	32.9%
	13	M2-D2	0.5%	0.3%	35.9%
	14	M2-D3	0%	0%	32.5%
	15	D2-R3	0.8%	0%	40.1%
	16	D2-R4	1.7%	0.2%	38.0%
	17	D3-R3	0%	0%	34.8%
	18	D3-R4	0%	0%	39.8%

4.6.2 Impact of disruption under Non-preemptive programming

In this section, all 18 scenario results are compared to the result of the base model solved by Non-preemptive Goal Programming, with equal weights on profit, backorders and risk. For each scenario, we get values of the three objectives after re-optimization, and calculate the differences from base model result. Table 4.22 and 4.23 present the impacts on both short term and long term disruptions using the non-preemptive GP model. In both tables, smaller numbers are better, representing smaller impacts on the objectives.

Table 4.22 Impact of Short-term Disruptions Compared to the Non-preemptive GP Base Model Results

Supply Chain component	Scenario	Disrupted Component	Reduced profit	Increased backorder	Increased risk
Supplier	1	S1	4.6%	0%	4.3%
	2	S4	0%	0%	0%
Manufacturer	3	M1	2.9%	9.7%	0.6%
	4	M2	4.5%	9.7%	11.3%
DC	5	D2	7.0%	4.7%	19.9%
	6	D3	0%	7.4%	0.2%
Transportation links	7	S1-M1	0.2%	0%	1.4%
	8	S1-M2	0.03%	0%	0%
	9	S4-M1	0%	0%	0%
	10	S4-M2	0.3%	0.2%	1.8%
	11	M1-D2	0.3%	1.5%	3.5%
	12	M1-D3	0.1%	0%	0.7%
	13	M2-D2	0.1%	0%	1.5%
	14	M2-D3	0%	0%	0%
	15	D2-R3	0%	0%	0%
	16	D2-R4	1.6%	0.9%	0.2%
	17	D3-R3	0.6%	1.4%	2.5%
	18	D3-R4	0%	0%	0%

From Table 4.22, a short-term disruption at S4 (scenario 2), transportation link S4-M1 (scenario 9), transportation link M2-D3 (scenario 14), transportation link D2-R3 (scenario 15), and transportation link D3-R4 (scenario 18) do not affect any of the objectives. However, a short-term disruption at the other facilities or transportation links leads to reduced profit, more backorders and more risk. Disruption at D2 (scenario 5) causes the most impact in terms of reduced profit (7.0%) and increased risk (19.9%). Disruption at M1 and M2 (scenario 3 and 4) cause the most impact in terms of increased backorders.

Table 4.23 presents the impact of long-term disruptions with respect to the base model results. The results show that the supply chain cannot reach the optimal solution when disruptions occur. In addition, disruptions at the facilities result in more negative impacts to the supply chain than the disruptions at the transportation links. Supplier S1, manufacturer M2 and distributor D2 are the top three facility disruptions causing the highest unfulfilled demand and profit reduction. Among all the transportation links, disruptions at the links connecting D2 and R4 (scenario 16) results in higher negative impacts to the supply chain in terms of profit, while disruptions at the links connecting S4 and M2 (scenario 10) results in higher negative impacts in terms of backorders and risk.

Table 4.23 Impact of Long-term Disruptions Compared to the Non-preemptive GP Base Model Results

Supply Chain component	**Scenario**	**Disrupted Component**	**Reduced profit**	**Increased backorder**	**Increased risk**
Supplier	1	S1	8.7%	0.4%	9.7%
	2	S4	0%	0%	0%
Manufacturer	3	M1	2.9%	1.0%	1.5%
	4	M2	4.8%	11.9%	10.1%
DC	5	D2	12.6%	4.7%	31.1%
	6	D3	0%	9.7%	0.4%
Transportation links	7	S1-M1	0.2%	0%	1.4%
	8	S1-M2	0.03%	0%	5.6%
	9	S4-M1	0%	0%	0%
	10	S4-M2	1.5%	2.6%	3.5%
	11	M1-D2	0.6%	2.5%	1.5%
	12	M1-D3	0.3%	0%	0.9%
	13	M2-D2	0.1%	0%	1.9%
	14	M2-D3	0%	0%	0%
	15	D2-R3	0%	0%	0%
	16	D2-R4	2.1%	1.4%	0.4%
	17	D3-R3	0.8%	1.4%	2.8%
	18	D3-R4	0%	0%	0%

4.7 Strategies to Mitigate Disruption Effects

There are many mitigation strategies that can be employed when disruptions happen. For illustration, we only choose four approaches to deal with supply chain disruptions. Table 4.24 lists them and their associated cost.

Table 4.24 Supply Chain Risk Mitigation Strategies

Disrupted facility or link	Mitigation strategies	Cost of Mitigation strategy
Supplier	Use of backup supplier	Fixed cost plus purchasing cost
Manufacturer	Keep extra finished products inventory at distributor	Extra inventory cost
Distributor	Purchase insurance	Insurance premium
Transportation link	Use other transportation mode	Fixed cost plus transportation cost

For each mitigation strategy, we will take one facility or link as an example to see whether using this strategy is cost effective when there is a disruption.

4.8 Results of Risk Mitigation Analysis

In this section, we analyze specific facilities and links, which cause high negative impacts, such as S1, M2, D2, and D2-R4. We will analyze potential risk mitigation strategies for those disruptions. For each case, we will use one risk mitigation strategy given in Table 4.24, and compare its effectiveness, with and without mitigation strategy, in terms of profit, backorders and risk.

<u>Case 1: Use of Backup Suppliers</u>

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 S1 is disrupted. We re-optimize the goal programming model under scenario 1 for two disruption durations. Under the normal situation (base model with no disruption), we should receive 1852 units of raw material from supplier 1, using the PGP model. Here we assume that the supply chain orders 1500 units from a backup supplier, and the cost of raw materials at the backup supplier is 100% higher than at Supplier 1. So the cost of purchasing raw material 1 is 81.32 $/unit, and that of raw material 2 is 29.82 $/unit. Under normal situation, 1892 units should be received from supplier 1 under the NPGP model, so we assume the same thing as the PGP model. Table 4.25 shows the changes in profit, backorders and risk with and without a backup supplier.

Table 4.25 Impact on Supply Chain Profit, Backorder and Risk under Case 1 (Supplier 1 is Disrupted)

GP Solution method	**Duration**	**Reduction in profit**		**Increase in Backorders**		**Risk Increase**	
		No backup supplier	With backup supplier	No backup supplier	With backup supplier	No backup supplier	With backup supplier
Preemptive	Short-term	4.1%	1.4%	0.5%	0%	42.9%	40.1%
	Long-term	8.1%	3.4%	0.5%	0%	46.1%	45.5%
Non-preemptive	Short-term	4.6%	1.5%	0%	0%	4.3%	7.5%
	Long-term	8.7%	2.5%	0.4%	0.2%	9.7%	5.5%

Table 4.25 shows that use of a backup supplier improves all the three objectives (profit, backorders and risk) under both short term and long term disruptions to Supplier S1. The only exception is the Non-preemptive GP model result for short term disruption for risk, where risk increases by using a backup supplier. Under a short-term disruption, using preemptive GP solution, we calculate that a backup supplier increases profit by $50,000, compared to scenario 1 with no risk mitigation, whereas it cost $31,240. Moreover, the supply chain risk and backorders decrease with mitigation. For the other three situations, calculated profits are greater than the cost, and hence, the use of a backup supplier is cost effective.

<u>Case 2: Keep Extra Finished Product Inventory at the Distributors</u>

We assume that the manufacturer could not produce any finished product during disruption, so the mitigation strategy is to increase the initial inventory at the distributors. For example, under short-term duration using preemptive GP method, 578 units of finished products are produced at manufacturer 2 during period 2. We assume that an additional 157 units in inventory are kept at all three distributors. Note that the additional inventory at the three DCs is only 471 units, less than 578 units needed, due to capacity restrictions at the DCs. We then re-optimize the model and get the new profit, backorders and risk. Table 4.26 shows the change in profit, backorders and risk with and without the extra inventory at the distributors.

Table 4.26 Impact on Supply Chain Profit, Backorder and Risk under Case 2 (Manufacturer 2 is Disrupted)

GP Solution method	**Duration**	**Reduction in profit**		**Increase in Backorder**		**Risk Increases**	
		No extra inventory	With extra inventory	No extra inventory	With extra inventory	No extra inventory	With extra inventory
Preemptive	Short-term	4.7%	4.3%	1.5%	0.9%	52.9%	44.4%
	Long-term	4.8%	4.5%	1.5%	0.9%	45.8%	45.0%
Non-preemptive	Short-term	4.5%	4.2%	9.7%	5.1%	11.3%	10.1%
	Long-term	4.8%	4.3%	11.9%	5.9%	10.1%	10.1%

From the result of Table 4.26, we see that there is no big improvement after applying risk mitigation strategy, only about 0.4% profit increase ($6669) is contributed by increasing initial distributor inventory. However, the cost of increasing inventory is far smaller than improved profit ($0.5 \times 157 = \$78.5$, where 0.5 represents the inventory holding cost per unit at distributor location, refer to Table 4.2). In terms of backorders, for the preemptive method, there is not much difference under short-term and long-term disruptions, while for the non-preemptive GP, increasing inventory could improve responsiveness, especially under long-term disruptions. This situation may be caused by high initial distributor inventory. In summary, keeping extra finished product inventory at the distributors increases the profit by $6590.50 and decreases the backorders and risk. Hence, this could be considered as an effective strategy when M2 is disrupted.

Case 3: Purchasing Insurance

Purchasing insurance represents the case where a company will do nothing when disruptions occur and just gets compensated for the financial loss. Here we assume that distributor DC2 is disrupted, the premium of purchasing insurance is \$11,000/year, and the compensation is \$130,000. Under this risk mitigation strategy, the increase in backorders and risk indices will not change (see Table 4.27). If the company puts emphasis on profit than responsiveness, then purchasing insurance may be a good strategy.

Table 4.27 Impact on Supply Chain Profit, Backorder and Risk under Case 3 (Distributor 2 is Disrupted)

GP Solution method	**Duration**	**Reduction in profit**		**Increase in Backorder**		**Risk increases**	
		No insurance	With insurance	No insurance	With insurance	No insurance	With insurance
Preemptive	Short-term	7.0%	0%	0%	0%	64.0%	64.0%
	Long-term	12.7%	5.6%	0.5%	0.5%	67.4%	67.4%
Non-preemptive	Short-term	7.0%	0%	4.7%	4.7%	19.9%	19.9%
	Long-term	12.6%	5.5%	4.7%	4.7%	31.1%	31.1%

From the results of Table 4.27, we see that under short-term disruption, the insurance could cover all financial loss, while under long-term disruption, the premium could only reduce part of the profit loss ($(12.7\% - 5.6\%) \times 1670399 = \$118{,}598$ under PGP model and $(12.6\% - 5.5\%) \times 1667146 = \$118{,}367$ under NPGP model). The optimal profit under PGP model is \$1551801 and that under NPGP model is \$1548778. Hence, if the disruption is short-term, this mitigation strategy could be considered. For long-term disruption at distributor 2, we should try other mitigation strategies.

Case 4: Use of Other Transportation Modes

Suppose the road transportation is often disrupted between distributor 2 and retailer 4 as mentioned in Chapter 3, and we consider the use of other transportation mode. Here we take rail transportation mode as an example, and then compare the results with and without the mitigation strategy. According to the original optimal solution, solved by the preemptive GP and non-preemptive GP methods, the quantity of finished products shipped from distributor 2 to retailer 4 using the road transportation mode in week 1 was 210. We will first set this variable to zero. Then, we set the quantity of finished products shipped from distributor 2 to retailer 4, using rail in week 1 as 210 under short term disruption. Similarly, we set the quantity of finished products shipped from distributor 2 to retailer 4, using rail in week 1 as 189, while setting the quantity of finished products shipped from distributor 2 to retailer 4, using road transportation mode in week 1 to zero under long-term disruption duration. In addition, we assume that the total fixed cost of shipping by rail is $1000.

Table 4.28 Impact on Supply Chain Profit, Backorder and Risk under Case 4 (road link D2 to R4 is Disrupted)

Solution method	**Duration**	**Profit**		**Backorder**		**Risk**	
		No mitigation strategy	With mitigation strategy	No mitigation strategy	With mitigation strategy	No mitigation strategy	With mitigation strategy
Preemptive Goal Programming	Short-term	-0.8%	0.6%	0%	-0.2%	32.2%	46.4%
	Long-term	-1.7%	0.6%	0.2%	-0.2%	38.0%	42.4%
Non-preemptive Goal Programming	Short-term	-1.6%	-0.6%	0.9%	-0.2%	0.2%	3.0%
	Long-term	-2.1%	-0.6%	1.4%	-0.2%	0.4%	0.8%

The positive sign in Table 4.28 refers to an increase and the negative sign refers to a decrease. For example, the first row indicates that if the road link between D2 and R4 is disrupted, profit will decrease by 0.8% (the optimal profit is $1669063), backorder will not change and risk will increase by 32.2%. After we choose the rail transportation mode, profit will increase by 0.6% (the optimal profit is $1671401) and backorder will decrease by 0.2%, but risk increases by 46.4%. The net increase in profit due to this mitigation strategy is $2339, which is greater than the fix cost $1000. This situation may be caused by the fact that the cost of rail transportation is lower than that of the road transportation, while the risk index (see Table 4.14) of rail transportation (3.811) is higher than that of road (2.447). According to the result of Table 4.26, we could conclude that using the other transportation mode is a good way to improve the resiliency of supply chain if managers put emphasis on profit and backorder rather than risk.

4.9 Conclusion

In this chapter, we demonstrate how to improve the resiliency of an existing supply chain network using a multi-criteria optimization model. In Sections 4.2 and 4.3, 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, backorders and risk. In Section 4.4, we perform a risk mitigation analysis to demonstrate the improvement to the supply chain resiliency under four risk mitigation strategies, backup supplier, extra inventory, insurance and use of other transportation modes.

Based on the analysis of four cases, two risk mitigation strategies (use of backup supplier, and use of other transportation mode) improve resiliency of the existing supply chain network, and they could be used for both short-term and long-term disruptions. For keeping extra inventory at the distributors when manufacturer is disrupted, the result shows that there is no significant improvement. Purchasing insurance is a good strategy for short-term disruption. In addition, we find that there is no significant difference between the results of preemptive and non-preemptive GP methods. Of course, the effectiveness of the risk mitigation strategies is only based on this numerical example, and cannot be generalized to any supply chain. However, we have illustrated how the risk mitigation analysis should be carried out to study its cost effectiveness.

Chapter 5

Conclusion and Further Research

5.1 Summary of the research

This thesis discusses how to incorporate disruption risks when making supply chain decisions in order to improve the resiliency of a supply chain. The main part is the vulnerability analysis and risk mitigation analysis based on a multi-criteria, multi-period, multi-stage supply chain network. The vulnerability analysis demonstrates the resiliency of the supply chain network operations under disruptions to a supply chain component. We use the READI method to study the impacts of disruptions under different scenarios. In Chapter 4, we provide a numerical example to show the vulnerability of each facility and link. Then a risk mitigation analysis is used to evaluate the effectiveness of risk mitigation strategies, such as a backup supplier and extra inventory.

5.2 Directions for future research

There are several possible extensions to the work presented in this thesis.

- Using other measures. Modeling responsiveness using the number of backorders at the retailer instead of using fill rate criteria or stock-out probability would provide a different perspective to analyze the model. Two objectives which are decreasing the number of backorder and increasing profit are less conflicting. Using other measures of responsiveness might improve the conflicting nature of the two objectives and the results may be different.
- Using stochastic demands and lead times. In this thesis, we have assumed these to be deterministic. This extension can be done by making suitable assumptions on the probability distribution of demand and lead time. This would make the model closer to practical situations.
- Considering the disruption of multiple supply chain components. In the vulnerability analysis, each disruptive scenario considers the disruption of only one supply chain component. Future research could consider the situation that multiple facilities or transportation links could be disrupted at the same time.

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