FLOOD RESILIENT SUPPLY CHAIN NETWORK DESIGN

BY

MR. VIDURA YASHODHA GAMAGE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING (LOGISTICS AND SUPPLY CHAIN SYSTEMS ENGINEERING)

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THESIS

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ENTITLED

FLOOD RESILIENT SUPPLY CHAIN NETWORK DESIGN

was approved as partial fulfillment of the requirements for
the degree of Master of Engineering (Logistics and Supply Chain Systems Engineering)

on May 12, 2020

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ABSTRACT

Modern supply chain is vastly expanded due to globalization and businesses evolving beyond countries and borders. Due to this nature of strong expansion in global supply chain, a failure in one supply chain component could cost millions of dollars. On the other hand, the global supply chain is more vulnerable to natural disasters more than ever with the infrastructural developments being carried out in the last few decades. A case of a small node failure could affect a large supply chain failure if the supplies are not managed properly during the time of failure. These few trends are the main reasons why many modern supply chain designers are focusing more and more on making the supply chain more resilient. More diverse supply chain networks are being designed around the world to ensure that the supply chain functioning is uninterrupted despite various nodes facing disruptions. Resilience in supply chain consists of two main strategies. Firstly, each and every organization in a global supply chain needs to minimize the risk of being disrupted by natural disasters and secondly, if an organization or a supply chain had to face the sequences of a disruption, it should have the ability to recover and get back to the normal working state as soon as possible with the smallest possible expense. "Resilience Triangle" is a concept that is used by many researchers as a way of understanding supply chain performance when faced with a disruption. Resilience triangle categorizes the performance of a supply chain into few phases and the supply chain analysts can consider each phase and the supply chain parameters related to each phase in order to uplift the performance. Basically this understanding helps the organization to ensure that they face the least damage if the organization is hit by a disruption and to recover in the quickest and best possible manner after facing the disruption. To analyze the potential risks to supply chain nodes, probability of failure can be utilized. The failure probability of each node can be connected to its geographical parameters when it comes to facing natural disasters. Another key supply chain decision in disruption management is the allocation of resilience budgets. This helps the system to accelerate the immediate response after facing a disruption. To analyze these parameters, building mathematical models is important. With the information gained from a mathematical analysis, the supply chain managers can directly make important supply chain decisions. Qualitative analyses too can only be evaluated if quantitative analyses are performed. Results from the quantitative analysis can be used to perform various further analyses such as comparing how the supply chain decisions change when resilience taken into consideration and not taken into consideration, how those parameters behave when the period of the disruption changes and the amount of budget.

Keywords: Supply chain, Disruption management, Flood, Resilient supply chain, Resilience triangle, Network design

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Mr. Vidura Yashodha Gamage

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Symbols/Abbreviations	Terms
SC	Supply chain
CC	Collection center
PP	Production plant

CHAPTER 1
INTRODUCTION

With the emergence of vast development projects and complex changes in infrastructure the world has started experiencing many natural disasters, making the supply chain vulnerable to many disruptions in the 21st century. South-east Asian countries have been a victim of various natural disasters over the years. Thailand, situated in the South-east Asia had to face a huge supply chain disruption when it was hit by a major flood back in 2011. Heavy and continuous rains were the main cause of the flood that left nearly fifteen million acres of land in disarray. These lands and properties belonged to 66 provinces of the country and consequences were experienced by 13 million people (The Ministry of Finance, Royal Thai Government & The World Bank, 2012). Until very recent past, consideration of probability of failure in supply chain disruption when making important supply chain decisions such as supplier selection, inventory planning etc. hasn't been much popular. In 21st century it was changed and many researchers and organizations have paid attention on considering the possible disruptions when making supply chain networks. Resilience of a typical supply chain is its capability to diminish potential risks, lessen the effect of a disaster to the organization over the human beings involved and infrastructure and accelerate the recovery actions when hit with a disastrous incident (Bruneau et al., 2003). There can be various methods and approaches of achieving the goal of making a resilient supply chain. Many of those methods suggest that the very first and most important step would be gaining knowledge to recognize the disruption scenario and the way it impacts the organization. A supply chain network design tool called "Resilience Triangle" would be the main concept discussed in this study which has been introduced as a way of understanding how the recovery process in an organization or a supply chain works under disruption uncertainties. The previous literature suggests that this concept can be utilized for both qualitative and quantitative analyses.

This concept makes understanding the situation of a disruption quite easy by categorizing the scenario into few main parts. Those selected parts can be addressed separately and the ease of addressing different stages helps not only mitigating the risks to avoid potential disruption, but also make a quick recovery in case of a worst case scenario where the organization gets disrupted badly. The resilience triangle would be explained and utilized in a case study of an agricultural supply chain in Eastern Thailand while considering the threat of flood to first conceptually examine the study and then consider the importance of various supply chain parameters and their behavior in supply chain network design to make a quantitative analysis.

1.1 Problem Statement

Supply chain resilience is a well-known term especially when making supply chain decisions in disaster prone areas. There are many factors to be taken into consideration related to both the organization and the disaster situation. In assessing supply chain resilience qualitative analyses and quantitative analyses are equally important. The best way to analyze a disruptive situation and an organization's performance during that time is by categorizing the scenario into few parts and analyzing them separately. Finding a relation between supply chain nodes' geographical parameters and their chance of being victim to a disruption is well established in literature. Improving an organization's readiness to face a disruptive situation is equally as important.

1.2 Research Objective

The objective of this study is to analyze the "Resilience Triangle" concept in a quantitative manner to find out how supply chain parameters such as vulnerability factors and capability factors behave in impact, degradation and recovery stages of a disruption. After analyzing the resilience triangle, the results would be compared to different scenarios to see the importance of different supply chain parameters in disruptive situations.

The study is motivated by the fact that the organizations are more vulnerable to disasters in the present due to new infrastructural advances. Due to this problem, making supply chain decisions considering only transportation costs wouldn't be sufficient. Even though resilience triangle has been considered in some studies in the past, no quantitative study has been performed considering all three stages of the resilience triangle namely impact, degradation and recovery, making this study a novel concept. This study applicable not only to fruit supply chains under flood threats in Thailand, but also to any supply chain under any disruption threats like earthquakes, hurricanes, tornadoes, volcanic eruptions, storms and Tsunamis. Therefore, this study is beneficial to any person or any organization looking to make their supply chain more resilient.

1.3 Research Methodology

The research methodology is to find out how the resilience triangle concept could be utilized to mathematically analyze the performance of an organization or a supply chain in a disruptive situation caused by a natural disaster. In this case a flood situation and the probability of failure concept are considered to find the vulnerability of supply chain nodes. In order to find the probability of failure the geographical parameters of the supply nodes are taken into consideration. Then to mathematically analyze the performance of the organization, distinctive characteristics of the flood and the geographical characters of the nodes are linked to each phase of the resilience triangle which will be discussed in chapter 3. In studying the resilience triangle and thereby minimizing the supply chain costs, the next important decision made in this study is finding the optimal resilience budget to be allocated by the supply chain nodes. Resilience budget is instrumental in making the recovery period shorter, making the supply chain more resilient.

1.4 Scope

Resilience triangle is a concept used to analyze the performance of a supply chain and its components by categorizing the disruption scenario faced by the supply chain into few parts. Based on the qualitative analyses and frameworks performed in the literature this study focuses on making a supply chain network design considering the various parts of the supply chain. In doing so concepts such as probability of failure, budget allocations will be taken into consideration. In analyzing the resilience triangle, the related parameters would be connected to geographical parameters of the supply chain nodes and the characteristics of the disaster. Finally, a mathematical model would be made to make supply chain decisions and the results are obtained. Using the obtained results various supply chain parameters' behavior and the importance in addressing supply chain resilience would be discussed.

1.5 Organization of the Thesis Report

Arrangement of the dissertation organization is as follows

1) Chapter 1 – Introduces the study and the importance of carrying it out, problem statement, the objective of the study, research methodology and the scope are explained.

2) Chapter 2 – Reviews the relevant literature in the context of resilience, resilience triangle. Previous work based on resilience triangle, both qualitative and quantitative analyses are explained.

3) Chapter 3 – Describes the study, explains the concept of resilience triangle further and explains how it can be cooperated in making a quantitative analysis, the case study is built and explained and the necessary data to validate the model are explained.

4) Chapter 4 – Builds the mathematical models based on chapter 3 in two steps to fulfil the research objectives, each parameter of the model is explained and elaborates the concept of using budget allocations.

5) Chapter 5 – Results are obtained using the data in chapter 3 and the model in chapter 4, Results are analyzed considering various scenarios and discusses the importance of considering various parameters and concepts in supply chain resilience.

6) Chapter 6 – Makes various conclusions based on the results, and suggests improvements to the concept, model and the case study as future work.

CHAPTER 2
REVIEW OF LITERATURE

When looking into previous studies it is evident there are many quantitative analyses performed compared to the qualitative analyses in the context of supply chain resilience. Even though lesser qualitative analyses are performed, they are similarly important since they provide the basis for many other quantitative analyses to follow. The importance of performing qualitative analyses in resilience was elaborated by Chowdhury, Maruf and Quaddus (2017) in their study and they introduced twelve parameters such as efficiency of a supply chain, readiness to a disruption, flexibility in operation, market strength etc. and described the ideal behavior of those parameters in making a resilient organization. Brusset and Teller (2017) performed a statistical analysis to further elaborate supply chain parameters using different survey results. The importance and practical applications of different strategical approaches in mitigating supply chain risks were discussed by Mensah and Merkuryev (2014) in another research. Vastly productive and popular quality related concepts such as lean, six-sigma were incorporated in their study to improve the resilience factor. Another qualitative framework was introduced by Saenz, Revilla and Acero (2018) in their study which was based on online survey results. They discussed about geographical parameters and other region specific parameters influencing an organization’s vulnerability to a disruption considering examples around the world. When making quantitative models and frameworks it is useful to study the previous work to find the research gap. The studies by Elleuch, Dafaoui, Elmhamedi, and Chabchoub, (2016) and Kamalahmadi and Parast (2016) performed such a study to analyze previous work to propose a new framework.

This paper considers the qualitative models that focus on resilience triangle concept. The concept of resilience triangle divides a given disruptive situation into a few major parts and analyze those parts separately to achieve the end goal of uplifting organization’s response to the disruptive scenario. The primary objective is to improve the performance after a disruption until it gets to its previous performance level or an even better performing level. This concept was first introduced by Bruneau et al. (2003).

The disruption was categorized into 3 major categories in their study and they were treated separately and the performance was measured separately according to the graph below. Three areas of the triangle were named as follows.

1) Impact - This is the immediate performance drop of an organization when it is hit by a disruption. The performance drops drastically during this period.
2) Degradation - During this period the dropped performance level nearly remains the same.
3) Recovery - During this period the organization starts launching the recovery process to get back to the preferred performance level.

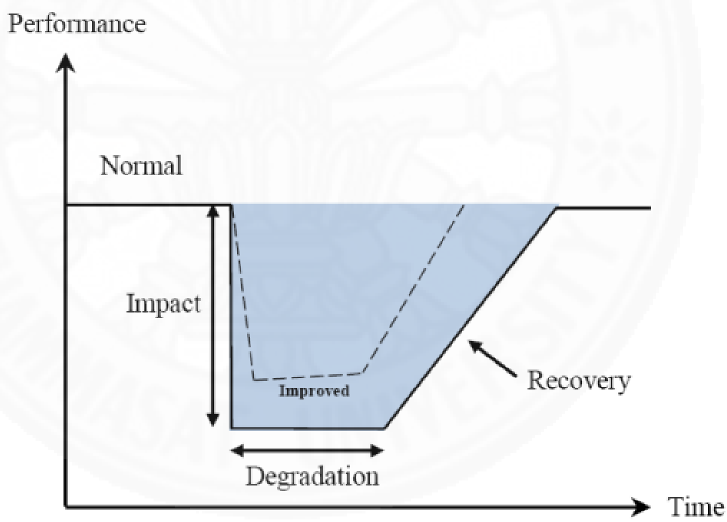

Figure 2.1: Resilience Triangle (Bruneau et al.)

The performance can be regulated by influencing various factors related to supply chain during each of these period. The general theory in considering the resilience triangle is that those supply chain parameters related to each period is considered and thereby minimize the area created by the resilience triangle to make the organization or the supply chain that the organization belongs to more resilient.

Chaidilok and Olapiriyakul (2017) made a framework where they categorized all the supply chain parameters into two groups by the names vulnerability factors and capability factors. They considered the phase in the resilient triangle they would be affecting. Then they elaborated how each of those parameters affect in Impact, Degradation and Recovery stages. According to the framework made by them different vulnerability and capability factors affected the system's response to the disastrous situation in different phases and addressing those parameters at the right time is extremely important and fruitful.

Another qualitative framework with a graphical representation was proposed by Duhamel, Châtelet, Santos and Birregah, (2012) for a complete performance of an organization in a disruptive situation. They considered two of the popular models in supply chain resilience namely PR^2 model and R^4 model. "PR^2" introduced by Haimes (2009) suggested 3 key resilient factors that affect in different stages of an organization's disruption management. Those 3 factors are;

- Preparedness
- Response
- Recovery

Operations as well as anticipation strategies of an organization would be the major elements in promoting the preparedness factor while various ways in overcoming the losses and having a satisfactory amount of resources play a key role in improving response and lastly in the recovery stage the rehabilitation process in the organization and the systemic operations carried on for the restoration process were considered when it has come across a major disastrous situation. The R4 model, introduced based on previous studies, Tierney and Bruneau (2007) and Bruneau et al. (2003), proposed four important parameters,

- Robustness
- Resourcefulness
- Redundancy
- Rapidity

Which would be beneficial in various parts of the resilience triangle for an improved supply chain performance in a disruptive situation.

Many researchers perform quantitative analyses for the ease of understanding how a system behaves comprehensively since those models explain everything numerically. In the context of supply chain resilience too it is easy to understand how the system performance behaves when the data can be represented numerically. There are many studies that have been developed considering various aspects of supply chain resilience in the past. Inventory allocation is one such key decision to be made considering the fact that the supply chain could face a disruption. One such problem was discussed with the risk of a potential disaster in an earlier study by Kristiano, Gunasekaran, Helo, and Hao (2014). The study also discusses about node allocation similar to this study prior to a potential disaster utilizing a method called "Fuzzy Shortest Path Method". In a previous analysis performed by Cardoso, Paula, Povoa, Relavas and Novais (2014), a novel parameter in the context of supply chain by the name "Expected Net Present Value" (ENPV) was introduced and defined and then a mathematical analysis was proposed to maximize the ENPV in the presence of disruption risks. Two more models followed a similar path as the study that is going to be presented in this paper. The mathematical models proposed in Fahimnia and Jabbarzadeh (2016) and Fattahi, Govindan and Keyvanshokooh (2017) minimize the total supply chain cost while considering various constraints according to disruption possibilities and other supply chain behaviors.

In one of the famous studies related to supply chain resilience performed by Snyder, Scapparra, Daskin and Church (2006), Reliable Facility Location Problem (RFLP) and a few similar mathematical models were introduced. With the objective function of minimizing the expected costs in supply chain, the RFLP model determines the facility location decisions in an optimal manner. The specialty of this study is that the concept of probability of failure has been utilized throughout the models described in this study to get a measure of the nodes which are at risk. Similar to this study they even assigned a penalty cost for unmet demands. The penalty cost could affect in different ways.

Despite making various models in the presence of a disruption threat and coming up with many qualitative frameworks for resilience triangle, not many used the resilience triangle concept as a tool to directly address the resilience in an organization to analyze system performance with the aid of mathematical model. The study, Montoya (2018) is one such scarce model that addressed various resilience related parameters of an organization by utilizing the resilience triangle as a tool. The main focus in this study is the last part of the resilience triangle which is the "Recovery Response". It utilized the resilience triangle proposed by Bruneau et al. (2003) to analyze the recovery stage and introduced the novel concept "investment level". Investment level depends on the ability of each organization and proved to be critical in the recovery process after a supply chain disruption. In Some other previous researches too such as Henry and Ramirez-Marquez (2012), Ouyang and Wang (2015), Baroud, Ramirez-Marquez, Barker and Rocco (2014), Bocchini and Frangopol (2010) and Cimellaro, Reinhorn and Bruneau (2010), the recovery phase of a resilience response has been addressed. Despite productively utilizing the resilience concept, one drawback of not using the all three stages of the concepts was visible in many of those studies. Therefore, utilization of all three stages of the resilience triangle was still an area to be discovered prior to performing this research.

CHAPTER 3
DESCRIPTION OF THE STUDY

The main objective of this study is to utilize the concept of resilience triangle as a tool in designing supply chain networks. Other than that, key supply chain resilience related concepts such as resilience budget allocation and using the concept of probability of failure is discussed in this study. This study consists of a mathematical model and a case study to evaluate supply chain decisions made in the presence of a supply chain disruption threat. There are two mathematical models presented in this paper, the second one being an improvement of the first model. The first mathematical analysis makes supply chain decisions such as selecting nodes and amount of goods to transfer while in the second model the initial model is developed to select resilience budgets for nodes as well.

To perform the above mentioned analyses, an agricultural supply chain in Thailand is considered as the case study. Thailand has a fame for being one of the leading suppliers of various fruits around the world. Thailand fruit supply chain is vastly expanded both locally and internationally. With the past experiences of being a victim to various flood situations, many supply chain network planners have started considering disruption threats when making supply chain networks. Following the trend of considering resilience when making supply chain networks, this study takes numerous related parameters into account while assuming a probable threat by floods. The agricultural supply chain considered in this study has mainly two components in the form of collection centers and production plants. Initial decisions to be made include selecting a production plant out of 3 probable options and make the selection of the most cost effective and resilient collection centers to collect the supplies from, taking numerous risks into consideration to minimize the total cost of the whole supply chain.

The responsibility of the aforementioned supply chain components are as follows. Collection Centers (CC) are responsible for the collection of fruits from farms and small scale local collectors, storing of fruits until they are prepared and the process of preparing them to send off to the production plants. Production Plants (PP) have the responsibility of determining the demand of fruits according to the demand from customers, making the decisions regarding supplier choice and the fraction of demand fulfilled by each customer and finally completing the whole production of preparing the fruits to be sent off to local and international customers. In the supply chain considered for this particular problem, the supply chain managers consider resilience too when making supply chain decisions compared to a typical supply chain where the supplier selection is based only on the distance between nodes and the transportation costs. Cost of a unit is assumed to be the same for all the collection centers in this problem.

Out of many concepts used in this study first one is the use of probability of failure. Probability of failure in a node can be defined as the chance of that node to be failed as a result of a disruption. Typically, probability of failure is linked to past data and information of supply chain nodes or can be related to some parameters such as altitude, build quality etc. In this case the probability is connected to the altitude of the collection centers since the flood disasters are considered in this study. Collection centers with higher altitude have a low probability to fail while the collection centers with low altitudes have a comparatively high chance of failure. In this case the failure probability would be calculated only for the collection centers to make the supply chain decisions.

Objective of this case study is to take make supply chain decisions while minimizing the total supply chain cost which consists of two typical supply chain costs and four cost parameters added to improve the disruption management capabilities of the supply chain. The first cost parameter is the transportation cost of products being moved from collection centers to production plants. The second cost parameter is the construction cost of the production plant in any chosen location. The third cost is the demand shortage and it occurs with the probability of failure. When the demand shortage occurs the production plant will have to gather the required amount of products from suppliers out of its supply chain which will be purchased at a much higher cost. Therefore, that additional cost is added as a penalty cost to the system. The next two cost parameters are directly related to the resilience triangle. The two areas of the resilience triangle would be added as cost parameters and it works as follows.

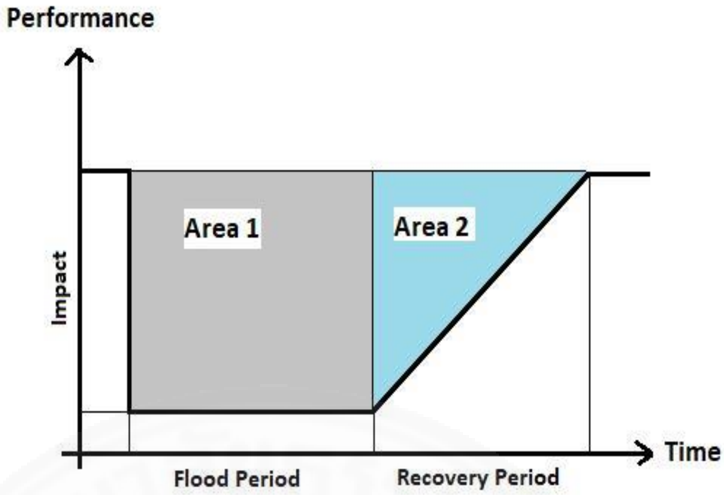

Figure 3.1: Resilience Triangle

As it can be seen in Figure 3.1 mainly there are two areas created by the three phases of the resilience triangle. Impact phase and degradation phase are accounted to the Area 1 while the impact phase and recovery phase are accounted to the Area 2. The purpose of studying this concept is to minimize the two supply chain costs incurred by the two areas of the triangle. Area 1 of the resilience triangle is calculated by,

Area 1 of the triangle = Impact * Flood Period (3.1)

Impact can be defined as a sudden fall in performance in the supply nodes caused by a flood scenario and the impact can be directly linked to geographical characteristics of a node which is the altitude in this particular study. Flood period is a parameter that cannot be controlled by any organization and fully depends on the severity of the precipitation. Area 2 of the resilience triangle is calculated by,

Area 2 of the triangle = 1/2*Impact * Recovery Period (3.2)

Like the equation 3.1, in the equation 3.2 too, the term impact means a sudden fall in performance in nodes when faced with a disruption while the term "recovery period" refers to the time taken by each supply chain node to get back to the preferred performance level which in this case depends on the resilience budget allocation level.

The fourth and fifth parameters which represent the areas in resilience triangle would be minimized in the objective function while sixth cost parameter represents the allocated resilience budget for the collection centers.

Map in Figure 3.2 shows the Eastern Thailand in which the supply chain components of this study are marked. The probable places of production plants marked in purple are situated in below mentioned locations as also mentioned in Gamage & Olapiriyakul (2020).

i) Kaeng-Hang-Maeo
ii) Sanam-chaiket
iii) Wang-sombun

while the collection centers that already exist to choose from, are mentioned below and marked in yellow in the map in Figure 3.2 as also mentioned in Gamage & Olapiriyakul (2020).

1) Prachin-buri
2) Chon-buri
3) Sattahip
4) Bang-khla
5) Bang-Pakong
6) Sakaeo
7) Ta-Phraya
8) Rayong
9) Klaeng
10) Wang-chan
11) Chantha-buri
12) Soi-Dao
13) Pong-Nam-Ron
14) Mueng-Trat
15) Khao-Saming
16) Bo-Rai

Out of the above mentioned locations the suppliers that minimizes the costs the most would be selected considering the typical costs with the addition of the resilience. A comparison with and without the influence of resilience too would be performed by using another supply chain model which does not consider resilience.

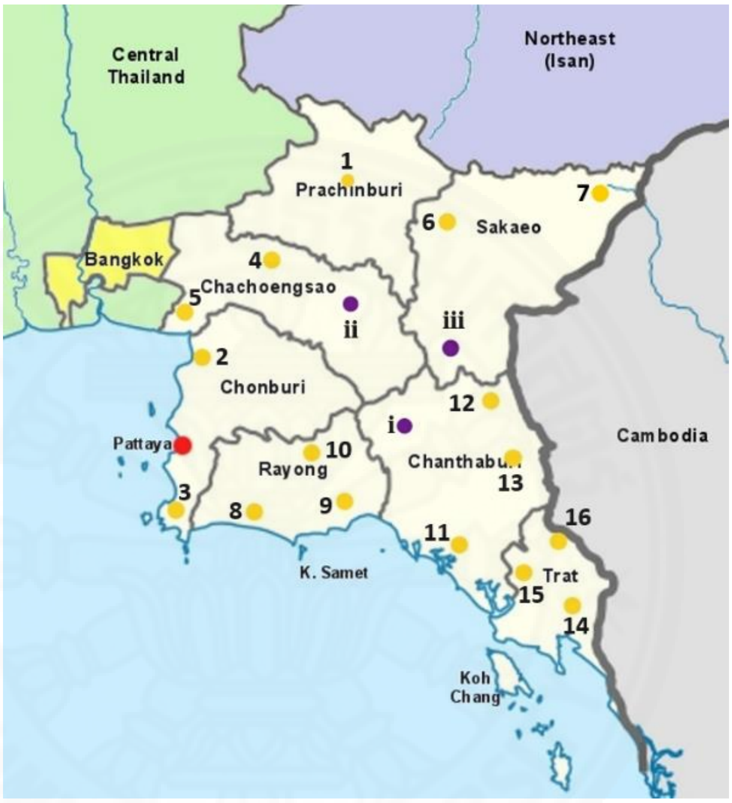

Figure 3.2: Map of Eastern Thailand, from Gamage & Olapiriyakul (2020)

Parameters that account to the model such as the altitude or elevation range, failure probability and Impact are mentioned in the Table I below.

Table 3.1: Input Parameters, from Gamage & Olapiriyakul (2020)

Collection Center	**Elevation Range (m)**	**Failure Probability**	**Impact (THB millions)**
Prachin-buri	24-25	0.1788	1.7921
Chon-buri	4-8	0.1951	1.9519
Sattahip	3-5	0.1969	1.9682

Bang-khla	2-4	0.1983	1.9757
Bang-Pakong	2	0.1982	1.9839
Sakaeo	35-39	0.1701	1.7042
Ta-Phraya	95-105	0.1204	1.2001
Rayong	6-12	0.1939	1.9358
Klaeng	13-15	0.1887	1.8879
Wang-chan	40-48	0.1652	1.6475
Chantha-buri	9	0.1929	1.9278
Soi-Dao	245-255	0	0.0201
Pong-Nam-Ron	237-241	0.0091	0.0880
Mueng-Trat	14-16	0.1879	1.8802
Khao-Saming	25-29	0.1778	1.7841
Bo-Rai	28-30	0.1776	1.7679

CHAPTER 4
MATHEMATICAL MODEL

4.1 Initial Mathematical Model

To make the supply chain decisions for the case study, an initial mathematical model similar to Gamage & Olapiriyakul (2020) was built. This model consists of two index sets for the collection centers and plants, three decision variables to choose the location to build the production plant and selects the suppliers out of 16 potential suppliers and decides the amount of products to receive from each supplier with the objective of minimizing the total supply chain cost. The supply chain cost parameters considered in this model are;

- Transportation cost
- Fixed construction cost of the production plant
- Demand shortage cost
- Costs incurred in the resilience triangle area 1
- Costs incurred in the resilience triangle area 2
- Cost of fixed resilience budget

The drawback of this model is that, this model does not have the ability to choose the optimal budget level which means that each collection center has to assign a pre-determined resilience budget. Therefore, this model had to be upgraded before extracting the results.

Index Sets

$m \in M$ CC or the collection centers

$n \in N$ PP or the Production plants

Parameters

d_{mn} Distance from CC to PP

C_m Capacity or the size of a CC

D_n Demand for each PP

k	Penalty cost (unsatisfied demand)
cc_n	Infrastructural Costs of PP
B_m	Allocation of resilience budget in CC
IM_m	Impact from a disruption to CC
FP	Span of the flood
RP_m	Time taken for recovery by each CC
q_m	Probability of failure
g	Cost of a unit of product

Decision Variables

$$X_n = \begin{cases} 1, & \text{if a plant is located} \\ 0, & \text{otherwise} \end{cases}$$

$$Z_m = \begin{cases} 1, & \text{if a collection center is utilized} \\ 0, & \text{otherwise} \end{cases}$$

s_{mn} Number of products shipped from CC

Minimize:

$$\sum_{m \in M} \sum_{n \in N} s_{mn}\, d_{mn}\, (1 - q_m)\, g + \sum_{n \in N} X_n cc_n + \sum_{m \in M} \sum_{n \in N} s_{mn}\, q_m\, k + \sum_{m \in M} q_m IM_m\, FP + \sum_{m \in M} (\tfrac{1}{2})\, q_m\, IM_m\, RP_m + \sum_{m \in M} Z_m B_m \quad (4.1)$$

Subject to:

$$\sum_{n \in N} X_n = 1 \quad (4.2)$$

$$\sum_{n \in N} s_{mn} \leq C_m Z_m, \quad \forall m \in M \quad (4.3)$$

$$\sum_{m \in M} s_{mn} = D_n X_n, \quad \forall n \in N \quad (4.4)$$

$$X_n \in \{1,0\}, \quad \forall n \in N \quad (4.5)$$

$$Z_m \in \{1,0\}, \quad \forall m \in M \quad (4.6)$$

$$s_{mn} \geq 0, \quad \forall m \in M, \ \forall n \in N \quad (4.7)$$

The objective function (4.1) considers resilience to minimize the total supply chain cost which consists of six components. Constraint (4.2) is for the choice of a location for the production plant (PP) out of the given options and the constraints (4.3) are the capacity constraints that state the number of products sent from each collection center cannot exceed its capacity or the size. Constraints (4.4) are to ensure that the demand set by each PP is achieved while constraints (4.5) and (4.6) denote the binary constraints. Finally, the Constraints (4.7) state that the amount shipped from a CC to a PP cannot be negative.

4.2 Final Model

This model is an improvement from the initial model where this has the ability to choose budget level from a few given choices. The budget choice directly has a connection with the time period an organization takes to recover from the disruption. Organizations with higher budget levels takes a short time period to recover while organizations with comparatively lower budget levels will take a longer time to recover making the connection indirectly proportional between the budget level and recovery period. Figure 4.1 and Table 4.1 show how the resilience budget level affects the recovery period.

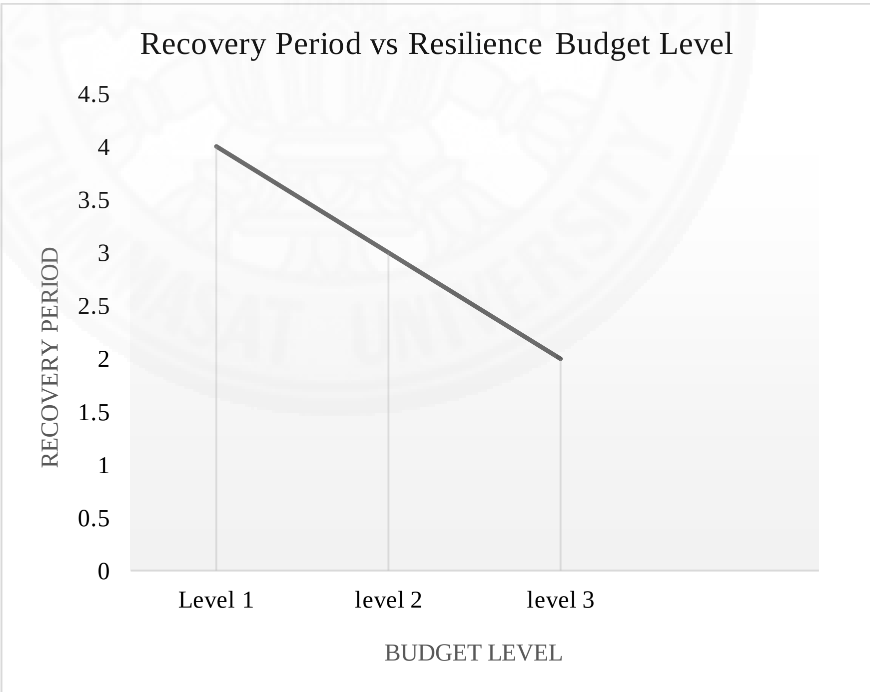

Figure 4.1: Recovery Period vs Budget Allocation

Table 4.1: Relationship Between Resilience Budget and Recovery Period

Resilience Budget Allocation 1000 THB	Resilience Budget Level	Recovery Period
200	1	4
250	2	3
300	3	2

This model consists of three index sets for the collection centers, plants and the level of resilience budget selected, three decision variables to choose the location to build the production plant, select the suppliers out of 16 potential suppliers and decide the amount of products to receive from each supplier with the objective of minimizing the total supply chain cost. The supply chain cost parameters considered in this model are;

- Transportation cost
- Fixed construction cost of the production plant
- Demand shortage cost
- Costs incurred in the resilience triangle area 1
- Costs incurred in the resilience triangle area 2
- Cost of fixed resilience budget

Index Sets

$m \in M$ CC or the collection centers

$n \in N$ PP or the production plants

$l \in L$ Budget levels

Parameters

d_{mn} Distance from CC to PP

C_m Capacity or the size of a CC

D_n Demand of each PP

k Penalty cost (unsatisfied demand)

cc_n	Infrastructural Costs of PP
B_{ml}	Allocation of resilience budget in each CC at each level
IM_m	Impact from a disruption to each CC
FP	Span of the flood (In terms of time periods)
RP_{ml}	Time taken for recovery by each CC at each budget level
q_m	Probability of failure
g	Cost of a unit of product

Decision Variables

$$X_n = \begin{cases} 1, & \text{if plant is located} \\ 0, & \text{otherwise} \end{cases}$$

$$Z_{ml} = \begin{cases} 1, & \text{if a collection center is utilized at each level} \\ 0, & \text{otherwise} \end{cases}$$

s_{mnl} Number of products shipped from CC to plants at each level

Minimize:

$$\sum_{m\in M}\sum_{n\in N}\sum_{l\in L} s_{mnl}\, d_{mn}\,(1-q_m)\, g + \sum_{n\in N} X_n cc_n + \sum_{m\in M}\sum_{n\in N}\sum_{l\in L} s_{mnl}\, q_m\, k + \sum_{m\in M} q_m IM_m\, FP + \sum_{m\in M}\sum_{l\in L}\left(\tfrac{1}{2}\right) q_m\, IM_m\, RP_{ml}\, Z_{ml} + \sum_{m\in M}\sum_{l\in L} Z_{ml} B_{ml}$$

(4.8)

Subject to:

$\sum_{n\in N} X_n = 1$ (4.9)

$\sum_{m\in M} s_{mnl} \leq C_m Z_{ml}, \quad \forall m \in M, \forall l \in L$ (4.10)

$\sum_{m\in M}\sum_{l\in L} s_{mnl} = D_n X_n, \quad \forall n \in N$ (4.11)

$\sum_{l\in L} Z_{ml} \leq 1 \quad \forall m \in M$ (4.12)

$X_n \in \{1,0\}, \quad \forall n \in N$ (4.13)

$Z_m \in \{1,0\}, \quad \forall m \in M$ (4.14)

$s_{mn} \geq 0 \quad \forall m \in M, \ \forall n \in N$ (4.15)

The objective function (4.8) considers resilience to minimize the total supply chain cost which consists of six components. Constraint (4.9) is for the choice of a location for a production plant (PP) out of the given options and constraints (4.10) are the capacity constraints that state the number of product units shipped from each collection center cannot surpass its capacity or the size. Constraints (4.11) are to ensure that the demand set by the production plant (PP) is achieved while constraints (4.12) are to choose only one level of budget allocation for each collection center. Constraints (4.13) and (4.14) denote the binary constraints. Finally, the constraints (4.15) state that the number of product units shipped from a collection center (CC) to a production plant (PP) cannot be negative.

CHAPTER 5
RESULTS ANALYSIS

This section contains the results analysis of the final model with the consideration of different scenarios. In the first section, the results of the final model are explained. In the second section those results are compared with the results from a typical supply chain model without resilience to see how various supply chain decisions change when resilience is considered and not considered. The third section of this analysis consists of a comparison of supply chain decisions made when the disruption period changes. The final section of this analysis shows whether the supply chain decisions vary when the different budget allocations are made for the collection centers.

5.1 Final Resilience Model Results

The final resilience model and the data have been fed into ILOG Cplex software to obtain the following results. Production plant selection, collection center choices, budget allocation level chosen by each chosen collection center and the supply chain costs are the main results being discussed in this section.

In the resilience model the production plant chosen is Wang sombun and the collection center choices and budget level choices are as follows.

Table 5.1: CC Selection and Budget Allocation

Collection Center	Collection Center Choice	Budget Allocation Level
Prachin-buri	✓	3
Chon-buri	×	×
Sattahip	×	×
Bang-khla	×	×
Bang-Pakong	×	×
Sakaeo	✓	3

Ta-Phraya	✓	3
Rayong	×	×
Klaeng	×	×
Wang-chan	✓	3
Chantha-buri	✓	3
Soi-Dao	✓	1
Pong-Nam-Ron	✓	1
Mueng-Trat	×	×
Khao-Saming	×	×
Bo-Rai	✓	3

Out of the chosen collection centers many collection centers have chosen the highest budget level (level 3) while Soi Dao and Pong Nam Ron have chosen the lowest budget level. Interestingly no collection center has chosen the medium budget level 2.

The map of the chosen supply chain is as follows. The chosen production plant is marked in purple while the collection centers are marked in yellow.

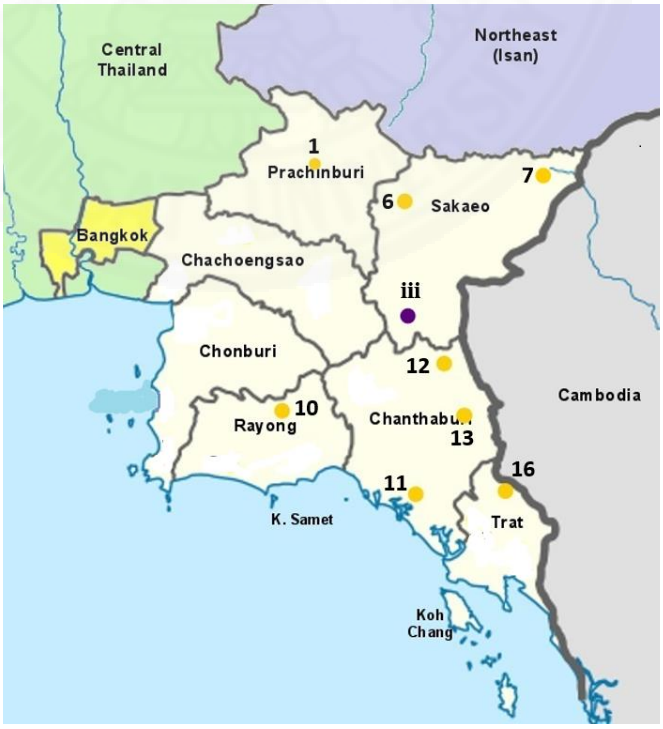

Figure 5.1: SC Map for the Final Model

Cost components of the model are listed below.

Table 5.2: Supply Chain Cost Components

Cost Component	Cost (million THB)
Transportation cost	987.73
Construction cost for PP	2.5
Shortage of Demand	709.1
Resilience triangle part 1	9.336
Resilience triangle part 2	1.713
Resilience budget	2.2

5.2 With and Without Resilience

In this section the resilience model we discussed earlier is considered with a typical non-resilient supply chain model to compare the results. Main results compared in this section are the production plant and collection center choices. “Sanam Chaiket” has been chosen by the model without resilience while “Wang Sombon” has been chosen by the model that considers resilience. The chosen collection centers by each model is mentioned below in the Table

Table 5.3: CC Selection with and without Resilience

Collection Center	Without Resilience	With Resilience
Prachin-buri	✓	✓
Chon-buri	✓	×
Sattahip	×	×
Bang-khla	✓	×
Bang-Pakong	✓	×
Sakaeo	✓	✓
Ta-Phraya	×	✓
Rayong	✓	×
Klaeng	✓	×

Wang-chan	✓	✓
Chantha-buri	×	✓
Soi-Dao	×	✓
Pong-Nam-Ron	×	✓
Mueng-Trat	×	×
Khao-Saming	×	×
Bo-Rai	×	✓

As you can see the both production plant and collection center choices are completely different between the non-resilient and resilient models. Therefore, the two supply chains look different highlighting the importance of considering resilience in supply chain network design. The maps of the two supply chains are as follows.

Figure 5.2: Supply Chain Map without Resilience

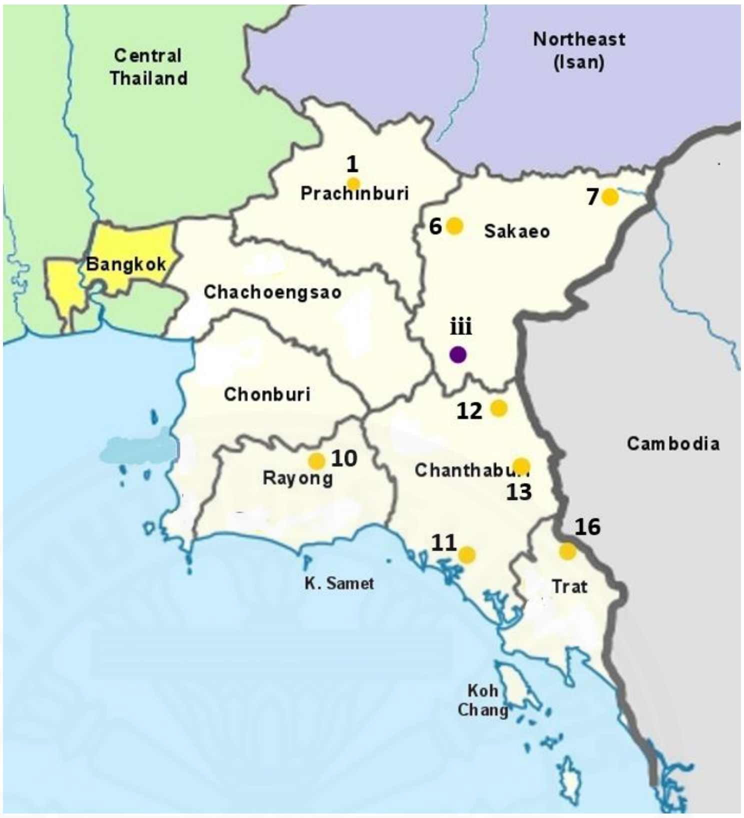

Figure 5.3: Supply Chain Map with Resilience

5.3 Flood Period

In this section the variation in results when the disruption period changes is considered. As mentioned earlier flood period is a character of the flood situation which is out of hands of supply chain managers and can depend on precipitation and many other natural factors. It is important to see whether the results deviate from one another when the flood period changes. The results show that the production plant choice for both the scenarios are Wang Sombun.

Table 5.4: SC Decisions with Different Disaster Periods

Collection Center	**Shorter Flood Period**		**Longer Flood Period**	
	Collection Center Choice	**Budget Allocation Level**	**Collection Center Choice**	**Budget Allocation Level**
Prachin-buri	✓	3	✓	3

Chon-buri	×	×	×	×
Sattahip	×	×	×	×
Bang-khla	×	×	×	×
Bang-Pakong	×	×	×	×
Sakaeo	✓	3	✓	3
Ta-Phraya	✓	3	✓	3
Rayong	×	×	×	×
Klaeng	×	×	×	×
Wang-chan	✓	3	✓	3
Chantha-buri	✓	3	✓	3
Soi-Dao	✓	1	✓	1
Pong-Nam-Ron	✓	1	✓	1
Mueng-Trat	×	×	×	×
Khao-Saming	×	×	×	×
Bo-Rai	✓	3	✓	3

According to the above results it is evident that the supply chain decisions considered, do not change from one another when the flood period changes. Regardless of the flood period considered, the production plant and collection center choices are identical, but most importantly even the resilience budget levels are identical too. Therefore, it is necessary to see how the costs related to resilience triangle changes despite no difference in other supply chain decisions.

With the identical results gained from the study the map of the supply chain does not change when the flood period is changed and the both supply chains look as follows

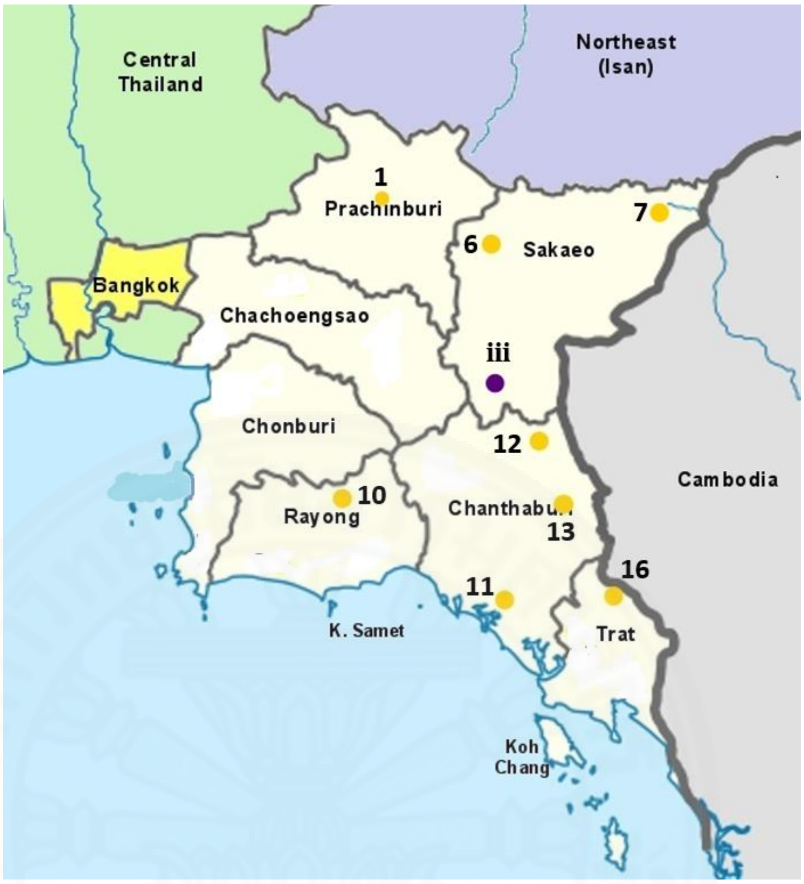

Figure 5.4: SC Map for Both Disaster Periods

Cost parameters of the two flood periods are as follows

Table 5.5: SC Costs with Different Disaster Periods

Cost Component	**Short flood period Cost (million THB)**	**Long flood period Cost (million THB)**
Transportation cost	987.73	987.73
Construction cost for PP	2.5	2.5
Shortage of Demand	709.1	709.1
Resilience triangle part 1	9.336	23.34
Resilience triangle part 2	1.713	1.713
Resilience budget	2.2	2.2

According to the above table, as expected the changes in flood period has affected the resilience triangle area 1. Despite making a noteworthy contribution the changes occurred in the resilience triangle area 1 is not enough to change any of the supply chain decisions.

5.4 Budget Allocation

In this section the main objective is to see whether there is a notable difference in supply chain decisions and cost parameters when the amount of resilience budget allocated to each collection center changes. To achieve that task a high and a low constant budgets are allocated to each collection center in two scenarios to see how the supply chain decisions and cost parameters change. Both scenarios chose Wang Sombun as the production plant location.

Table 5.6: CC Selections with Different Budget Allocations

Collection Center	**Low Budget**	**High Budget**
Prachin-buri	✓	✓
Chon-buri	×	×
Sattahip	×	×
Bang-khla	×	×
Bang-Pakong	×	×
Sakaeo	✓	✓
Ta-Phraya	✓	✓
Rayong	×	×
Klaeng	×	×
Wang-chan	✓	✓
Chantha-buri	✓	✓
Soi-Dao	✓	✓
Pong-Nam-Ron	✓	✓
Mueng-Trat	×	×

Khao-Saming	×	×
Bo-Rai	✓	✓

According to the above results we can clearly see that there's no difference in supply chain decisions when the allocated budget is changed from one another. The map of both the scenarios are the same due to same supply chain decisions.

Figure 5.5: SC Map for both Budget Levels

Cost parameters of the two scenarios are as follows

Table 5.7: SC Costs with Different Budget Allocations

Cost Component	Low Budget Cost (million THB)	High Budget Cost (million THB)
Transportation cost	987.73	987.73
Construction cost for PP	2.5	2.5
Shortage of Demand	709.1	709.1
Resilience triangle part 1	9.336	9.336
Resilience triangle part 2	3.4244	1.7122
Resilience budget	0.8	4
Total Cost	1712.9	1714.4

As you can see the different budgets have influenced two cost parameters, namely resilience budget costs and resilience triangle part 2. When a low budget is set the recovery period by the organization is longer compared to when a high budget is set. Anyhow it seems setting a high resilience budget seems to be a bit costlier according to the above results.

CHAPTER 6
CONCLUSION AND FUTURE WORK

When the results section is carefully analyzed it is evident that the resilience related cost parameters have notably impacted the total costs. Collection center (CC) choices, production plant (PP) choices as well as total costs are totally different when the resilient model and the non-resilient models are compared. These results lead us to the conclusion that the contribution by the resilience related parameters in supply chain network design is significant. It could also be stated that if the supply chains are designed without the consideration of resilience in areas like in Thailand which are highly prone to disasters, the costs would be so high if they come across any unpredicted disruptions. According to the results tables, the main decisive factor when making decisions by the non-resilient model is “distance” between the collection centers (CC) and production plants (PP) and it changes to geographical parameters rather than the distance when the decisions are made using the resilient model which hints the importance of considering resilience. Considering the differences between the two separate analyses, the concept of “Resilience Triangle” can be seen as a potent tool in supply chain network design for the future.

Even though the supply chain decisions changed significantly when resilient model and non-resilient model were compared, no notable difference was evident when the disruption period was changed. Costs related to resilience triangle changed a bit but it was not enough to change any of the supply chain decisions and it leads us to the conclusion that the period of the disruption does not really affect the supply chain decisions made using the resilience triangle. It was the same case with low and high budget allocations as well. When a high budget is allocated the nodes tend to recover quickly compared to a lower budget. Therefore, a difference between costs was evident but not enough evidence to state that the level budgets has a significant impact on supply chain decisions in a disruption.

As future work it would be interesting to validate the same concept and the same model in a different supply chain and or in a different area with different geographical parameters to see the results have a similar pattern. Applying the same concept to a different disaster other than floods would be another area for future researches. Also it would be interesting to further analyze each supply chain parameter and how the supply chain decisions would change according to the changes made for those parameters.

Another suggestion for future work would be to consider many geographical and other related factors when considering the probability of failure. Since this study considers a simplified version of a supply chain it would be interesting to see the differences in supply chain decisions when applied to a more complex and a more realistic supply chain. Costs can be reduced further too using more complex methods.

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APPENDIX

APPENDIX A
NON-RESILIENT SUPPLY CHAIN MODEL

<u>Index Sets</u>

$m \in M$ CC or the collection centers

$n \in N$ PP or the production plants

<u>Parameters</u>

d_{mn} Distance from CC to PP

C_m Capacity or the size of a CC

D_n Demand of each PP

cc_n Infrastructure costs of PP

g Cost of a unit of product

<u>Decision Variables</u>

$X_n = \begin{cases} 1, & \text{if plant is located} \\ 0, & \text{otherwise} \end{cases}$

$Z_m = \begin{cases} 1, & \text{if a collection center is utilized} \\ 0, & \text{otherwise} \end{cases}$

s_{mn} Number of products shipped from CC to PP

Minimize:

$$\sum_{m\in M}\sum_{n\in N} s_{mn}\, d_{mn}\, g + \sum_{n\in N} X_n cc_n \qquad (1)$$

Subject to:

$$\sum_{n\in N} X_n = 1 \qquad (2)$$

$$\sum_{n\in N} s_{mn} \le C_m Z_m, \quad \forall m \in M \qquad (3)$$

$$\sum_{m\in M} s_{mn} = D_n X_n, \quad \forall n \in N \qquad (4)$$

$$X_n \in \{1,0\}, \quad \forall n \in N \qquad (5)$$

$$Z_m \in \{1,0\}, \quad \forall m \in M \qquad (6)$$

$$s_{mn} \ge 0, \quad \forall m \in M, \ \forall n \in N \qquad (7)$$

The objective function (1) minimizes the total supply chain cost which consists of two components, transportation cost and production plant construction cost. Constraint (2) is for the choice of a location for the production plant (PP) out of the given options and constraints (3) are the capacity constraints that state the number of product units sent from each collection center cannot exceed its size or the capacity. Constraints (4) are to ensure that the demand set by the production plant is achieved while constraints (5) and (6) denote the binary constraints. Finally, constraints (7) state that the amount transferred from a collection center to a production plant cannot be negative.

BIOGRAPHY

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