Multistage Logistic Network Optimization under Disruption Risk

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ABSTRACT

Getting over disruptions risk has been a challenging issue for many companies under the globalization that will link to potential external source such as demand uncertainties, natural disasters, and terrorist attacks. The disruption is an unexpected event that disturbs normal flows of products and materials within a supply chain. The disruption at one members of supply chain will propagate the offers and finally affect significant impacts on the entire chain. If we look back at the natural disasters in the recent decade, we know the supply chain activities have been put at the edge of high risk that bring catastrophic impact to companies. Not only such disruptions in the supply chain are increasing in frequency, but also the severity of their impact is escalating in terms of costs and losses. Since they will eventually bring a company a partial or complete halt, it is avoidable to consider disruption as a potential threat to supply chain and logistic network. Thereat, we can anticipate the disruption by considering preventive action to ensure the supply chain. If the supply chain takes preventive action against the disruption, such action is viewed as mitigation planning.

In this research, we analyzed possible strategies that a company can apply to mitigate and minimize the impacts of supply chain disruptions and design supply chain network in which facilities are unreliable by considering the fact that the facility members may fail. Failure of the facility means that the facility is no longer available to serve its customers. When these facilities

happen to fail, the concerned organization has to find alternate sources of supply to continue service to the customers, to reroute assignments that were initially intended or to incur large penalties.

To cope with the problem, we are interested in a three echelon logistic networks composed of distribution center (DC), relay station (RS) and Customer. Thereat, we consider two kinds of relay station like reliable relay station (RRS) and unreliable relay station (URS). The URS is subject to failures and the reliable relay station (RRS) becomes the hardened ones by having additional capacity or external alternative sourcing strategy. So it is more expensive to establish or operate such facility compared to URS. If the primary facility is disrupted, however, RRS will act as backup facilities to provide supply of product to customers.

Under those conditions, we formulate the logistic optimization problem so that the expected total cost associated with disruption probability is minimized under various constraints. It refers to a probabilistic mixed-integer programming problem. Then, this dissertation concerned three main problems.

The first problem considers three types of allocation model, i.e., multi-multi allocation, multi-single allocation and single-single allocation model. Taking these models, we compared some properties among three allocation models which have different configurations of the network. This is because the configuration is one of the most important and strategic issues in the logistic network design that has long lasted effect. Concern with this issue, we carried out a morphological analysis in order to measure the complexity of the multi stage logistic networks besides the expected cost. Finally, numerical experiment is carried out by applying commercial software to validate the proposed idea.

The operational level of the company will decrease below the normal condition when disruption occurs. The backup source after the disruption should be recovered not only as soon as possible, but also as much as possible. This is related to the concept of the business continuity management/plan

(BCM/P) to reduce the recovery time objective. The second problem considers a robust supply chain network design by considering the effect of continuity rate to cope with the more practical circumstances. That is to say, we assume that URS is not completely halted and RRS will decrease the backup ability depending on the continuity rate of facility. Eventually, the continuity rate is percentage of ability facility to provide backup allocation to customers in abnormal situation and will affect the investment and operational costs. We evaluated the effect of the continuity rate for the foregoing three models. Finally, numerical experiment is carried out to derive some prospects for the future studies.

In the real-world situation, we need to concern huge numbers of facility members that make the resulting problem extremely difficult to solve. Accordingly, with increasing problems size, it becomes almost impossible to solve the problem by any currently available software. In the last problem, therefore, we developed an effective hybrid method so that we can solve the problem regardless of the size. The approach is composed of meta-heuristic method like tabu search and graph algorithm. Some bench mark problems are solved to validate the effectiveness.

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Chapter 1

INTRODUCTION

1.1 Background

Supply chain disruptions have been a challenging issue for companies under the globalization environment. They are unplanned and unanticipated events that disrupt the normal flow of products and materials within a supply chain. The disruption at one members of supply chain can result significant impact on the entire chain. Supply chains are subject to potential external sources of disruption such as natural disasters and terrorist attacks. Research has been conducted by Kleindorfer and Saad (2005) and Wagner and Bode (2007) to illustrate the high priority supply chain disruptions should be in supply chain management. However, there is still a lot of work to be done in measuring the effects of disruptions on supply chain performance.

If we look back at the natural disasters in the last few years such as the latest earthquake and tsunami in Japan in March 2011, devastating floods in Thailand, and an extreme winter in Europe in early 2012, companies have been put at the edge of high risk due to frequent natural events that bring catastrophic impact to companies. Issues mentioned above can bring devastating impacts on the company's operations and particular on its supply chain and logistics.

As an example when earthquake and tsunami in Japan caused dramatic impact on the supply chains and logistic distribution of many companies, including those in the automotive, electronics and chemical industries. The resulting slowdowns and cessation of operations affected seriously some companies. For example, a Hitachi factory that produces electronic components for European car maker was disrupted by this disaster. As a consequence, a certain European maker was argued to slow the production due to shortage of material from Hitachi.

We can anticipate the disruption by considering preventive action to ensure the supply chain is not adversely affected. If the supply chain takes preventive action against the disruption, such action is viewed as mitigation planning. Under such mitigation plan, the supply chain can build a robust system that will minimize the impact of the disruption in the future. One such mitigation mechanism would be to have backup facilities that may provide supplies if the primary facility would be disrupted. Schmitt (2011) recommended that one of the best protections can be achieved through backup capabilities that will protect the supply chain until the disruption’s end and prevent long or permanent interruptions to customer.

In line with a growing trend of natural disasters the complex and long supply chain due to increasing pressure to source globally and to exploit lower manufacturing costs made it even more difficult to avoid supply chain risks. The complexity of products and processes are also adding to the probability of disruptions.

Although an organization cannot prevent the occurrence of natural disasters, it can prevent or reduce the risk of damage from them. There are many tools and measures that an organization can apply in advance such as supply chain risk mapping and risk assessment to identify its characteristics of the supply chain flows (Xanthopoulos *et al*. 2012). Global companies tend to have more experience in dealing with disruption with more alternative arrangements as their sourcing activities are expanding. Meanwhile, it is necessary for companies to redesign a resilient supply chain strategically that resists the effect of a disruption.

1.2 Objectives of thesis

The objectives of this thesis are concerned with developing a robustly designed supply chain network that takes into account contingency plans in the event of disruption and providing a framework that consists of the strategies and analytics in designing supply chain networks to hedge against disruptions.

In this research, we analyzed possible strategies that a company can apply to mitigate and minimize the impacts of supply chain disruptions and design supply chain network in which some facilities are unreliable by considering the fact that facilities (such as manufacturing plants and warehouses) can fail. Failure of the facility means that the facility is no longer available to serve its customers. When these facilities fail, the concerned organization has to find alternate sources of supply to provide service to the customers and/or reroute assignments that were initially intended to go to a particular warehouses or retail location or incur large penalties. When a supply chain is poorly configured, finding alternate supply sources and rerouting shipments can be very expensive. In this study, we focus on issues related to facility disruptions. This is because facility disruptions are likely to be more critical than other supply chain drivers such as transportation, procurement, production, inventory, distribution, and routing.

The occurrence of any disruption is thus stochastic, so preventive measures can be taken to anticipate the disruption to ensure that the supply chain is not adversely affected. If a supply chain takes preventive measures in anticipation of a disruption then such actions are referred to as mitigation planning. Under a mitigation plan, the supply chain tries to build a robust system that can minimize the ill-effects of the disruption which is expected to happen at some point in the future. Having backup suppliers and manufacturers is a part of the mitigation mechanism that provides supplies in the event when the facility is disrupted. Such cases are considered in Tomlin (2006) where a supply is considered from two suppliers one of which is reliable, but expensive, while the other is unreliable but cheap.

Mitigation planning of such kind is very popular in industries where the possibility of disruption is high, and it may cause immense financial ruin to the supply chain if they do not have backup source of supplies. Such was the case as demonstrated in Tomlin (2006) where he discussed the difference between Ericsson’s and Nokia’s strategies after the supply line for some parts for the cellular phone market was disrupted at their supplier, Phillip’s facilities. Nokia was able to minimize its losses by having a robust supply chain in the place where it could get its supplies from secondary suppliers. Meanwhile, Ericsson suffered a huge loss during this period because it had not anticipated this disruption and could not get the necessary supplies from elsewhere. This is just one of the numerous examples that demonstrate the need for some mitigation planning in place for the supply chains to remain competitive and profitable in the marketplace.

In spite of all the preventive actions, if disruptions do occur, proper policy changes should be made among the various members of the supply chain so that the supply chain can be brought back to its normal level relatively quickly. This field of study that deals with policy changes that a supply chain should take after a disruption has taken place is called contingency planning. In this research, we introduce the concept of business continuity management/plan as a part of the contingency planning in the event of disruptions.

The definition of business continuity management/plan is a holistic management process that identifies potential impacts that threaten an organization and provides a framework for building resilience and the capability for an effective response to ensure that the recovery process is achievable without significant disruption to an organization (Gibb and Buchanan 2006).

Since every problem in this study is formulated as a mixed integer programming, a hybrid tabu search approach as heuristics method is applied to account for large-size problems.

We summarize the objective of this research as follows:

1. Comparing allocation models for multistage logistic network considering disruption risk.
2. Introducing morphological analysis for multistage logistic network considering disruption risk.
3. Proposing continuity rate as a part of business continuity plan approach.
4. Proposing an effective hybrid method composed of the metaheuristic method and graph algorithms to offset potential losses from network disruption.

1.3 Overview of the thesis

This thesis composed of seven chapters. The first chapter describes the introduction. It includes background, objectives of the thesis and overview of the thesis. Chapter two concerns with literature review. This review includes the supply chain management concept, supply chain risk management concept, supply chain disruption, risk driver of supply chain, and supply chain risk mitigation.

Chapter three concerns about comparison of multistage logistics network designs. Chapter four describes the morphological analysis. Chapter five focuses on effect of continuity rate. Chapter six concerns about hybrid approach for huge multi-multi allocation model. The conclusion and recommendation for further study is lastly presented in Chapter seven.

Chapter 2

LITERATURE REVIEW

2.1 Supply Chain Management

Modern supply chains today are becoming longer and more complex due to increasing market globalization (Thomas and Griffin 1996). Longer and complex supply chains are much more vulnerable to disruptions risk, which influence throughout the network and make planning more difficult. Robust and flexible supply chain designs become a significant consideration to the decision maker.

A supply chain is a system of facilities or a network of entities such as manufacturers, suppliers and distributors are working together to provide product to the end customers since raw material to finished product. Chen and Paulraj (2004) provide an illustration of a company supply chain which consists of a network of materials, information, and services processing links with the characteristics of supply, transformation and demand as shown in Figure 2.1.

In the 1990s, the concept supply chain management (SCM) was appeared to express the need to integrate the key business processes, from end user through original suppliers. Original suppliers are those that provide products, services and information that add value for customers and other stakeholders. Harland (1996) describes supply chain management (SCM) as managing business activities and relationships (1) internally within an organization; (2) with immediate suppliers, (3) with first and second-tier suppliers and customers along the supply chain, and (4) with the entire supply chain. The main purpose to apply the concept of SCM to the organization is to produced the product and distributed at the right quantities, to the right locations and at the right time, in order to minimize system wide costs (or maximize profits) while satisfying service level requirements.

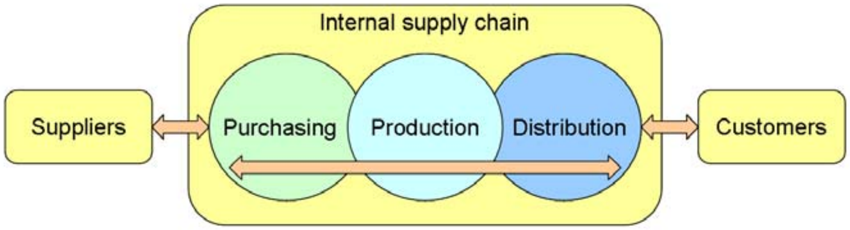


Figure 2.1: An illustration of a company's supply chain

The basic idea behind the SCM is that companies and corporations involve themselves in a supply chain by exchanging information regarding market fluctuations and production capabilities. Supply chain decisions include: Which suppliers should we use? How many manufacturers and distributors should we have and where should we locate them? How do we determine the capacity at each location? What products should manufacturers produce? Given locations and capacities, supply chain decisions will then try to answer questions such as the following: what quantities should we produce and store at these locations? What quantities should be moved from location to location and at what time? (Shen 2007).

One of the crucial planning activities in SCM is to design configuration of the supply chain network. In SCM, there are three planning levels, namely strategic, tactical and operational, which usually distinguished depending on the time horizon (Melo *et al.* 2009). The planning of the strategic level includes determining the number, location, capacity and technology of the facilities and the tactical/operational level involves determining the quantities of purchasing, production, distribution, product handling and inventory holding as well as transportation between established facilities. The configuration of the supply chain is the key strategic decision that influences activities at a tactical/operational level and has long-lasting effect on network (Shen 2007). Therefore, the fact that a supply chain network design (SCND) problem invests a large amount of capital for new facilities become an important issue.

Organizations as well as entire supply chain network become more vulnerable against disruption risks. Therefore, it is essential for organizations in supply chain to agree on a common risk management approach in their network design. One drawback of SCM is the assumption that process will run under normal conditions without considering potential risks that might occur. Risk can be arising from the supply side, demand side as well as from facility side become great a concern in today’s business environment. The concept of the supply chain risk management has been developed in the literature and practice to handle this risk.

2.2 Supply Chain Risk Management

Companies have to offer a wide range of different products or variants in order to satisfy customer demand which leads to higher vulnerability due to higher complexity (Harland *et al.* 2003). Furthermore, companies can no longer afford to focus on local markets. They are forced to realize the potential of global markets in terms of suppliers as well as customers resulting in a highly complex supply chain. Due to a high interconnectedness of companies and trend towards globalization within complex networks, supply chains have become more vulnerable for risk disruptions.

Supply chain risk is recognized in today’s economy as a major threat to business continuity. A disruption in the supply chain can reduce a company’s revenue, decrease its market share, inflate costs, or threaten production and distribution. In recent years, many companies implement the concept of supply chain risk management (SCRM) to enhance the resilience against the disruption risk. According to Wieland and Wallenburg (2012), SCRM can be defined as the implementation of strategies to manage both everyday and exceptional risks along the supply chain based on continuous risk assessment with the objective of reducing vulnerability and ensuring continuity.

A common classification of supply chain risk was classified into five sources according to their origin. These five sources can be summarized in three groups: company internal risks, supply chain internal risks, and environmental risks as depicted in Figure 2.2 (Christopher and Peck 2004). Two risk sources, process and control risks, are located within the company considered. These sources cover all risks emerging out of production and logistics processes as well as managerial risks, which fulfill the definition of supply chain risks. The second group consists of two other risk sources, supply and demand risks. These sources contain all risks emitted by supply chain partners, thus all indirect supply chain risks. The last group is formed by the environmental risks. These risks represent all potential damage caused by socio-political, macroeconomic or natural disasters.

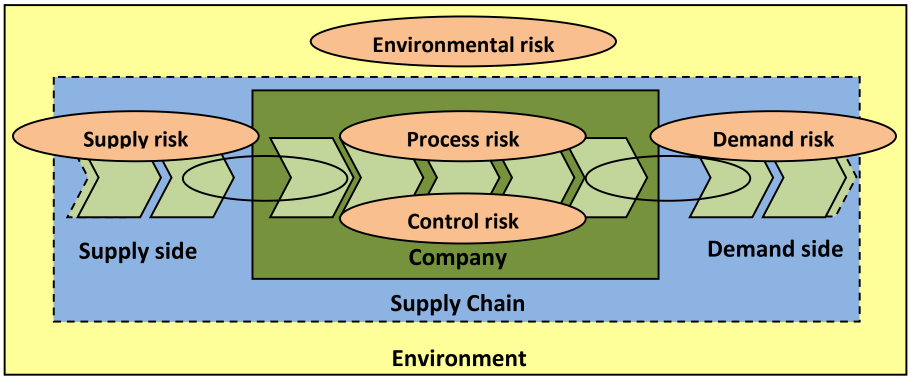


Figure 2.2: Source of risk within supply chain

According to Chopra and Sodhi (2004), the supply chain risks could be in the form of delays of materials from suppliers, large forecast errors, system breakdowns, capacity issues, inventory problems, and disruptions. Another classification which is categorized supply chain risks into operations and disruptions risks (Tang, 2006). The operations risks are associated with uncertainties inherent in a supply chain, which include demand, supply, and cost uncertainties while disruption risks are those caused by major natural and man-made disasters such as flood, earthquake, tsunami, and major economic crisis. Tang (2006) reviewed SCRM articles, but the author focused on quantitative models. The author classified articles according to four basic supply chain areas: supply management, product management, information management, and demand management.

Risk and uncertainty has always been an important issue in supply chain management. Earlier literature consider risks in relation to supply lead time reliability, price uncertainty, and demand volatility which lead to the need for safety stock, inventory pooling strategy, order split to suppliers, and various contract and hedging strategies (Tang 2006). The author believes that effective SCRM has become a need for companies nowadays.

Several words mostly mention on related to SCRM concept in various ways: *robustness*, *flexibility* and *resilience*. The difference between robustness, flexibility and resilience is illustrated in the figure 2.3 (Husdal 2009). The ability to survive (*resilience*) is likely to be more important in a business setting than the ability to regain stability (*robustness*) or the ability to change course (*flexibility or agility*) quickly. Supply chain risk management must include all.

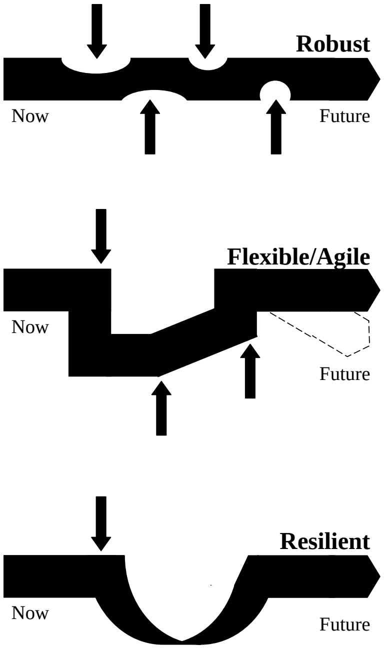


Figure 2.3: Illustration of Flexibility or agility, robustness and resilience

2.3 Supply Chain Disruptions

Supply chain disruptions are unplanned events that can affect the normal, expected flow of materials, information, and products, and are recognized as inevitability within a supply chain organization (Svensson, 2002). A disruption event is the manifestation of risk within the supply chain process.

This is not a matter of a supply chain system encountering a problem, but rather a matter of when a problematic event will occur and the severity of the event. Therefore, the study of risk, interdependence, and the associated impact of a disruption on supply chain performance is a growing area of interest to many as they strive to reduce their organization’s risk of disruption.

There are some previous studies about supply chain risk considering disruption risk. For instances, the research of Tomlin (2006) investigates the impact of considering unreliable facilities for the facility location problems. Snyder and Daskin (2005) and Lim *et al.* (2009) have introduced facility location model, in which facility may fail with given probability while Chopra and Sodhi (2004) and Kleindorfer and Saad (2005) studied the risk management perspective on supply chain disruption.

Supply chain disruption can be the result of large-scale natural disaster, terrorist attacks, plant fires, electrical blackouts, financial or political crises, and many other scenarios. Supply chain disruptions are the enemy of all companies for, both potential and actual condition. Definition of disruption in term of the supply chain context is unplanned and unanticipated events that disrupt the normal flow of products and materials within a supply chain (Craighead *et al*. 2007). Some well-known examples of supply chain disruptions include:

- The 1999 earthquake in Taiwan had a dramatic impact on the global semiconductor market. At the time, Taiwan was the third largest supplier of computer peripherals in the word, so the earthquake caused a temporary global shortage of semiconductor components with the production down times that ranged from 2-4 weeks. Production and sales of many firms were profoundly affected by this shortage (Bundschuh *et al*. 2003).
- On March17, 2000, a small fire occurred at a Philips semiconductor plant in Albuquerque, the New Mexico. Even though, the plant was

burned for only 10 minutes but production process was halted. Nearly half of the factory's output was destined for two Europe's biggest cell phone makers, Nokia and Ericsson. When Nokia and Ericsson received information about the fire at the following day, they were informed that there would be minimal disruption. In fact, the factory took several months to return to full production (Sheffi 2001).

- On March 11, 2011, Tohoku area in Japan was struck by a 9.0-magnitude earthquake and follow by the massive tsunami. General Motors had to halt the production of vehicles at several plants, due to parts shortages from Japanese suppliers. Also, Toyota had to suspend production of parts in the mother country that were intended to be shipped overseas. Finally, most Japanese automotive assembly plants remain closed (Azad 2012).

Consequences of supply chain disruptions might be financial losses, a negative corporate image or a bad reputation eventually accompanied by a loss in demand as well as damages in security and health (Juttner *et al.* 2003). The MIT Research Group on "Supply Chain Response to Global Terrorism" identifies six different levels of disruption in the context of supply chain management (Rice *et al.* 2003). See Table 2.1.

Over the last several decades, significant effort has been expended in making supply chains leaner and cheaper. However, recent studies point out that while this effort has successfully reduced operational costs, unfortunately, it has also increased the vulnerability of supply chains (Rice *et al.* 2003). While companies are often used to dealing with supply chain risks arising at the operational level, many suffer much heavily from supply chain disruptions. Although supply chain disruptions occur with low probability, the consequences are usually catastrophic. Kleindorfer and Saad (2005) showed that disruption risks are fundamentally different from the risks arising from machine failures or demand uncertainties because they totally stop the production and are likely to persist for a long period of time. The importance of disruption risk is also highlighted by Hendricks and Singhal (2005) who show that supply chain disruptions expose a firm to negative financial impacts; recovering from such shocks is typically very slow.

Table 2.1: Categories of supply chain disruptions

Failure Mode	Description
Disruption in Supply	Delay or unavailability of materials from suppliers leading to a shortage of inputs that could paralyze the activity the activity of the company
Disruption in Transportation	Delay or unavailability of the transportation infrastructure leading to the impossibility to move goods, either inbound and outbound
Disruption at Facilities	Delay or unavailability of plants, warehouses and office buildings hampering the ability to continue operations
Freight breaches	Violation of the integrity of cargoes and products, leading to the loss or adulteration of goods (can be due either to theft or tampering with criminal purpose, e.g. smuggling weapons inside containers)
Disruptions in communications	Delay or unavailability of the information and communication infrastructures, either within or outside the company, leading to the inability to coordinate operations and execute transactions
Disruption in Demand	Delay or disruption downstream can lead to the loss of demand temporarily or permanently, thus affecting all the companies upstream

2.4 Risk Drivers of Supply Chain

It is essential for constructing a resilient logistic network to capture the properties of risk imbedded thereat. Such risks are classified into three categories listed below.

- Outside risk refers to abnormal climate, natural disaster, change/enactment of law/regulation, riot, terrorism and exhaustion of resources, etc.
- Inside risk is
    - caused by inbound logistics such as: crash; problems associated with quality, safety, productivity, tardiness and delivery of raw materials and parts; strike, scandal; violation of laws and regulations, etc.
    - caused by outbound logistics such as: unexpected change of demand; problems from order processing and solvency; frequent deviations of specification, etc.

- Risk caused within the company refers to
    - those peculiar to operations incidents, malfunctioning of production, human errors, etc.
    - those caused by management and decision making, safety level of inventory, schedule of delivery, location/allocation of sites/resources, etc.

Cao and Chu (2010) provide classification of the risk driver in the supply chain in order to understand the conventional studies in a well-organized manner and to have a definite prospect in the future as shown in Table 2.2. In particular, they claim the importance of organizational cooperation over the society. Looking at the recent worldwide affairs, it makes sense prepare against various disruption risks and move on undertaking a suitable Business Continuity Plan/Management (BCP/BCM). This is also a consequence guided from the “All over the processes” row in the table. As a summary of this section, the importance of backup system for supply chain is well understandable for this purpose.

2.5 Supply Chain Risk Mitigation

Risk mitigation is to mitigate the uncertainties identified from the various disruption risk sources by undertaking some strategic move deliberately (Miller 1992). There are many strategies for mitigating disruption risks. Oke and Golapalakrishnana (2009) suggested some kinds of measure to mitigate supply risks, such as better planning and co-ordination of supply and demand, flexible capacity, identifying supply chain vulnerability points and having a contingency plan and multiple sourcing strategy. In the general classification of mitigation strategy for disruption risk are contingency plan, robust optimization and stochastic models.

Tabel 2.2: Classification of risk driver

Attribute Process	Quality	Cost	Due date	Environment	Flexibility	Evaluation	Strategy
Development				36, 37		11	11, 13, 14, 32
Procurement		6, 18, 34		35, 36, 37	5, 6, 7, 33, 39		25, 28, 31, 32
Production		6, 34		35, 36, 37, 40	5, 6, 7, 26, 33		25, 26, 28, 31, 32
Distribution		6, 34		35, 36, 37, 40	5, 6, 7, 33		25, 28, 31, 32
Sales	30	6, 12, 30, 34	30	35, 36, 37, 40	5, 6, 7, 8, 33		25, 28, 31, 32
Interface for processes	3, 4	3, 15, 22	1, 3, 17, 24, 29		2, 15, 19		
All over the processes	38	9, 21, 38	9, 20, 38	38	23, 38		10, 16, 23, 27

1: Delay, 2: Number of available supplier, 3: Supply availability, 4: Quality, 5: Inventory availability, 6: Capacity, 7: Inventory management, 8: Volume, product mix and requirement change, 9: Disruption, 10: Intellectual property, 11: Environmental performance, 12: Fluctuation in market prices, 13: Process technology change, 14: Product design change, 15: Receivables, 16: System trouble, 17: Information system compatibility and sophistication, 18: Procurement, 19: Cycle time, 20: Inbound transportation, 21: Cost reduction capabilities, 22: Financial health of supplier, 23: Forecast, 24: Shipment quantity inaccuracies, 25: Management vision, 26: Capacity constraints, 27: Strategic risk, 28: Operations Ask, 29: Supply Risk, 30: Customer Ask, 31: Asset impairment, 32: Competitive risk, 33: Reputation, 34: Financial risk, 35: Fiscal risk, 36: Regulatory risk, 37: Legal risk, 38: Disaster, 39: Hazardous substances, 40: Recycle

2.5.1 Contingency Planning

Contingency planning is a risk management tool, and the aim is to minimize the impact of an upcoming event and show how the business will resume normal operations after the event of disruption. In business continuity and risk management, a contingency planning is a process that prepares an organization to respond the unplanned event. For simple definition, a contingency plan is can be referred to as "Plan B".

Contingency planning in supply chain has become a significant issue for manufacturers and distributors because supply chains are getting leaner, distances are growing longer and natural disasters such as earthquakes and hurricanes are always a threat. Lean supply chains eliminate inventory that in the past provided some buffer for unexpected events. Contingency planning in supply chain begins with identifying the potential risks. We have shown the categories of supply chain disruptions in Table 1 section 2.3.

In the context of the recovering from a supply chain disruption, both Ericsson and Nokia were facing supply shortage of critical cellular phone component (radio frequency chips) after Philip's Electronics semiconductor plant in New Mexico caught on fire in March 2000. Philip's informed Ericsson and Nokia that it was not possible to deliver certain components for a certain period after fire accident. Nokia recovers quickly by deploying a contingency plan to reconfigure the design of their generic cellular phone. So that, by this phone modification, Nokia can accept slightly a component that was different from the one being delivered by the Philips's plant. The concept of product flexibility is applied by Nokia affecting recover easily from serious disruption. Nokia can provide difference product based on the generic cell phone without any significant problem. Consequently, Nokia satisfied customer demand and obtained a stronger market position. On the contrary, Ericsson was unable to deploy a similar strategy and it loss $400 million in sales (Hopkins 2005).

2.5.2 Robust Optimization

Robust optimization is another approach to handle uncertainty in the planning stage. The philosophy of robust optimization is to help companies to reduce cost and/or improve customer satisfaction under normal circumstances and sustain their operations during and after disruption.

Tang (2006b) presented some robust strategies as listed below.

- *Postponement*; utilizes product or process design concept such as standardization, commonality, modular design and operational reversal. (Increase product flexibility).

  For example, Nokia deployed a contingency plan by reconfigure its generic cell phone quickly to allow slightly different components.
- *Strategic Stock*; instead of carrying more safety stocks, a company may consider keeping some inventories at certain strategic locations to be shared by multiple supply chain partners (Increases product availability).

  For example, CDC keeps large quantities of medicine and medical supplies at certain strategic locations in USA.
- *Flexible Supply Base*; To use more than two production bases, one for volume and the other for the excess in order to mitigate the risk associated with single sourcing (increases supply flexibility).

  For example, HP used Singapore plant as the base volume and Washington one to produce the excess of the base volume.
- *Make-and-Buy*; Supply chain more resilient if certain products are manufactured in-house while others are outsourced to other suppliers (increases supply flexibility).

  For example, Zara produce their fashion item at their in-house factories and outsource other basic items to their suppliers in China.

- *Economic Supply Incentives*; Used at the condition that there are very limited numbers of suppliers available in the market (increases product availability).

  For example, Supplier offered economic incentives by US government to re-enter the flu vaccine market by sharing some financial risks and committing to a certain quantity in advance at a certain price and buying the unsold products again at a lower price when the flu season end.
- *Flexible Transportation*; Transportation is the Achilles' heel and consider adding more flexibilities in a proactive manner (increase flexibility in transportation).

  For example, Multi-modal transportation (trucks, motorcycles, bicycles, ships and helicopters), multi-carrier transportation and multiple routes.
- *Revenue Management via dynamic pricing*; Dynamic pricing is a common mechanism for selling perishable products/services (increases control of product demand).

  For example, Dell offered special *low-cost-upgrade* options to customers if similar computers with components from other supplier were chosen after an earthquake happened in 1999 and disrupted its Taiwan supplier.
- *Assortment Planning*; Reconfiguring the set of products on display, location on the shelves and number of facings for each product to manipulate customer's product choice and demand (increases control of product demand).

  For example, five supermarkets in USA suggest that one can utilize this strategy to entice customers to purchase widely available products when certain ones are facing SC disruptions.
- *Silent Product Rollover*; under this strategy, new products are leaked slowly into the market without any formal announcement (increase control of product exposure to customers)

> For example, Swatch produces each watch model only once and launches new products so that its customers will view all available ones as collectibles by utilizing this approach.

The advantages of robust strategies are that they can guarantee the performance of the supply chain regardless of the occurrence of major disruptions. Prevention is better than cure, if the company can reduce their exposure to risk by considering supply chain alliance network, lead time reduction and recovery planning system.

2.5.3 Stochastic Models

Stochastic model is a typical method of generating and operational plan within an uncertain environment when the precise probability distribution of future uncertainty is known in advance.

The common type of stochastic disruption appearing in the literature is supply disruption. Schmitt (2008) developed a stochastic model considering supply disruption include the impact to industry and demonstrate mitigation strategy in supply chain. Goh *et al*. (2007) develop a multistage stochastic model for supply chain network by providing a general formulation of the multi-stage supply chain network problem operating under a scenario of a variety of risks. The goal is to optimize distribution logistics and facility location planning in an international setting.

Chapter 3

COMPARISON OF MULTISTAGE LOGISTIC NETWORK DESIGNS

3.1 Introduction

As the development of economic globalization, worldwide logistics become imperative for the business world especially by global company that services supported by universal supply chain. How to manage logistics system efficiently has become an important issue for many companies to reduce their total costs. In general, total cost is defined as the sum of production, supply, inventory, transportation, and facility costs.

The traditional multistage logistics networks problem is defined as a set of facilities including potential suppliers, potential plant facilities, and distribution centers (DCs) and a set of customers with deterministic demands. The main purpose of this problem is to determine the configuration of the production and distribution system between facilities in order to satisfy the customer demands and the profit of the company is maximized or the total cost is minimized (Goetschalckx *et al*. 2002). The network structure of the traditional logistic problem is like that shown in Figure 3.1.

In this study, we focus on the issue related to facility disruption risk for multistage logistic networks and present three different kinds of allocation model each of which will provide a robust design. The proposed allocation models are multi-multi allocation (MMA) model, multi-single allocation model (MSA) and single-single allocation (SSA) model. The aim of this study is to compare the properties among these allocation models. In the MMA model, each Relay Station (RS) will receive the product from multiple DCs and customers also from multiple RSs depending on the respective demand of the customer. In the MSA model, RSs will receive the product from multiple DCs while customers only from one RS. In the SSA model, each RS can receive just from a single DC, and each customer also receives from a single RS. Figure 3.2 shows the difference between the models.

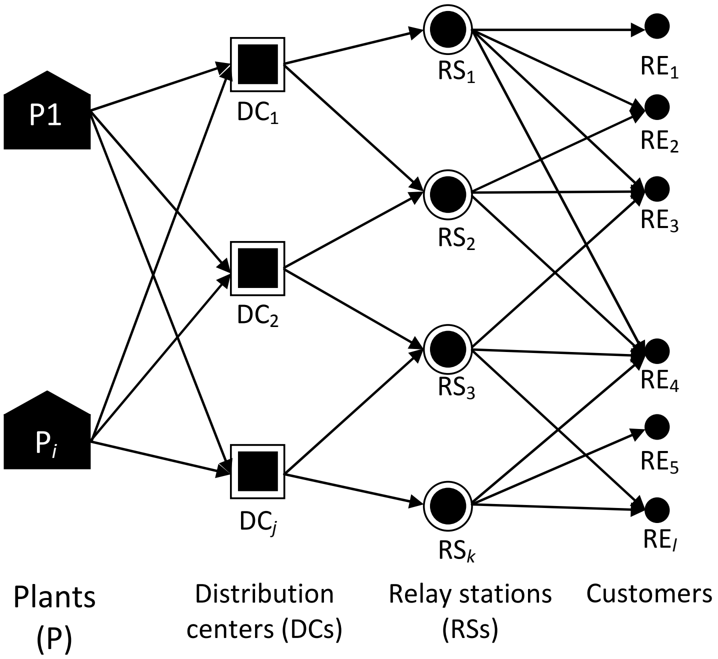


Figure 3.1: The structure of traditional multistage logistic network

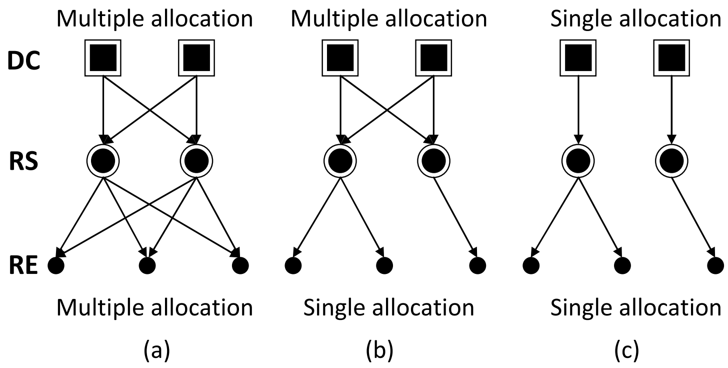


Figure 3.2: Allocation model; (a) MMA (b) MSA (c) SSA

Previous research takes only account of two echelon logistic problems as explained in Chapter 2 section 2.3. In a real word application, logistic network design can be proposed as multistage problem. Therefore, we define the problem as a multistage logistic network designs problem.

A three echelon problem consists of a set of distribution centers (DCs), a set of relay stations (RSs) and a set of customers (REs). The location decisions are made in the RS level. In RS level, we proposed two kinds of RS the reliable RS (RRS) and unreliable RS (URS). An unreliable relay station (URS) is subject to failures. Failure of the RS means that RS is no longer available to serve customers. When RS fails, the firm has to find alternate sources of supply to provide service to customers. A reliable relay station (RRS) has additional capacity and or an external alternative sourcing strategy. By default, it is more expensive to establish or operate RRSs compare to URSs.

Figure 3.3 illustrates the multistage logistic network where RS is potentially being disrupted. Two DCs distribute products to three relay stations (RSs), which consist of two RRS and one URS. If the demand of the customer is satisfied by RRSs, then only one assignment is available for both primary and backup assignments. On the other hand, if the customer is assigned to URSs, backup assignment is required besides the primary assignment. This means when the disruption occurs at URS, the demand of customer will be distributed from RRS which is assigned as the backup.

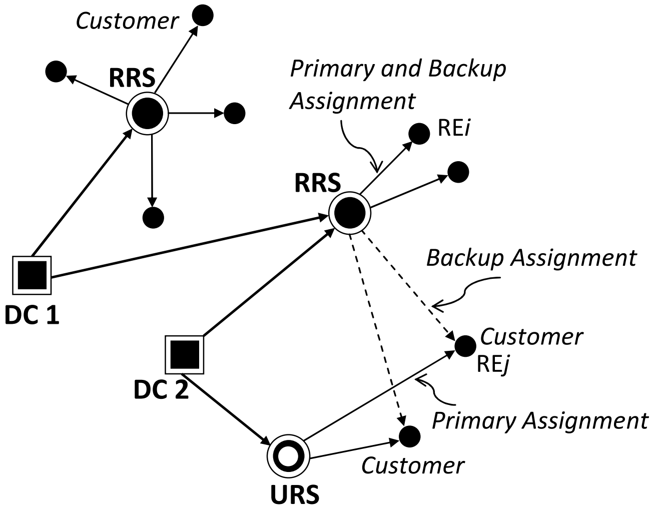


Figure 3.3: Illustration of logistic network model under disruption risk

3.2 Problem Formulation

In this section, we present a Mixed-Integer Programming formulation for each of the proposed allocation models. The objective is to minimize total cost by properly locating reliable and unreliable facilities. The expected total costs that consists of fixed costs for opening RSs, shipping costs at DCs, transportation costs between each DCs to RSs and RSs to customers and handling cost at each RS. In these models, each customer $k \in K$ has a demand d_k. The product is distributed from DC I to RS J and from RS J to customers K, respectively. At each customer k, we may locate either RRS with opening cost F_j^R or URS with opening cost F_j^U. Fixed cost for opening RRS is higher than URS ($F_j^R > F_j^U$) due to an undisrupted reason.

The transportation cost per unit demand from DC I to RS J is given by $T1_{ij}^P$ and $T1_{ij}^B$ for primary assignment and backup assignment, respectively.

We also consider the relation $T1_{ij}^{P} < T1_{ij}^{B}$ due the consequence of using the backup resources. Similarly, the transportation cost per unit demand from RS to the customer is given by $T2_{jk}^{P}$ and $T2_{jk}^{B}$ for primary assignment and backup assignment, respectively. We also assume the relation $T2_{jk}^{P} < T2_{jk}^{B}$ due to the consequence of using the backup resources.

Moreover, the handling cost at each RS is denoted as H_k^P and H_k^B for primary and backup condition, respectively. We assume that the relation $H_k^P < H_k^B$. In this model, we assume the probability of disruption which is denoted by q_j ($0<q_j<1$). Primary assignments occur with probability $1-q_j$ under the normal cost while backup assignments occur with probability q_j under the abnormal cost.

The following notations are used to describe the mathematical model.

Index set

I : set of distribution centers (DC)
J : set of relay stations (RS)
K : set of customers (RE)

Parameters

F_j^U : Fixed cost for opening URS j
F_j^R : Fixed cost for opening RRS j
C_i^P : Shipping cost at DC i as primary assignment
C_i^B : Shipping cost at DC i as backup assignment
H_j^P : Handling cost at RS j as primary assignment
H_j^B : Handling cost at RS j as backup assignment
$T1_{ij}^P$: Transport cost from DC i to RS j as primary assignment

$T1_{ij}^{B}$: Transport cost from DC i to RS j as backup assignment

$T2_{jk}^{P}$: Transport cost from RS j to customer k as primary assignment

$T2_{jk}^{B}$: Transport cost from RRS j to customer k as backup assignment

U_j : Capacity of RS j

PU_i : Maximum supply ability of DC i

PL_i : Minimum supply ability of DC i

d_k : Demand of customer k

q_j : Probability of disruption RS j $(0 < q_j < 1)$

Decision variable

a_{ij}^{P} : Shipped amount from DC i to RS j as primary assignment

a_{ij}^{B} : Shipped amount from DC i to RS j as backup assignment

b_{jk}^{P} : Shipped amount from RS j to customer k as primary assignment

b_{jk}^{B} : Shipped amount from RS j to customer k as backup assignment

$$x_j^U = \begin{cases} 1, & if\ RS\ j\ is\ opened\ as\ unreliable\ one; \\ 0, & otherwise. \end{cases}$$

$$x_j^R = \begin{cases} 1, & if\ RS\ j\ is\ opened\ as\ reliable\ one; \\ 0, & otherwise. \end{cases}$$

$$y_{jk}^P = \begin{cases} 1, & if\ RS\ j\ disributes\ customer\ k\ as\ primary\ assingment; \\ 0, & otherwise. \end{cases}$$

$$y_{jk}^B = \begin{cases} 1, & if\ RS\ j\ disributes\ customer\ k\ as\ backup\ assingment; \\ 0, & otherwise. \end{cases}$$

$$z_{ij}^P = \begin{cases} 1, & if\ DC\ i\ disributes\ RS\ j\ as\ primary\ assingment; \\ 0, & otherwise. \end{cases}$$

$$z_{ij}^B = \begin{cases} 1, & if\ DC\ i\ disributes\ RS\ j\ as\ backup\ assingment; \\ 0, & otherwise. \end{cases}$$

3.2.1 Multi-multi allocation model (MMA Model)

In this model, we consider each RS will receive the product from multiple DCs and customer also from multiple RSs depending on the respective demand of the customer. The model for MMA is described as follows.

Minimize

$$\sum_{j\in J} F_j^U x_j^U + \sum_{j\in J} F_j^R x_j^R$$

$$+\sum_{j\in J}(1-q_j)\left(\sum_{i\in I}(C_i^P + T1_{ij}^P)a_{ij}^P + \sum_{k\in K}(H_j^P + T2_{jk}^P)b_{jk}^P\right)$$

$$+\sum_{j\in J} q_j\left(\sum_{i\in I}(C_i^B + T1_{ij}^B)a_{ij}^B + \sum_{k\in K}(H_j^B + T2_{jk}^B)b_{jk}^B\right) \tag{3.1}$$

Subject to:

$$x_j^U + x_j^R \le 1 \qquad \forall j \in J \tag{3.2}$$

$$\sum_{j\in J} x_j^R \ge 1 \tag{3.3}$$

$$\sum_{i\in I} a_{ij}^P \le U_j(x_j^U + x_j^R) \qquad \forall j \in J \tag{3.4}$$

$$\sum_{i\in I} a_{ij}^B \le U_j x_j^R \qquad \forall j \in J \tag{3.5}$$

$$\sum_{j \in J} a_{ij}^{P} \leq PU_i \qquad \forall i \in I \tag{3.6}$$

$$\sum_{j \in J} a_{ij}^{B} \leq PU_i \qquad \forall i \in I \tag{3.7}$$

$$\sum_{j \in J} a_{ij}^{P} \geq PL_i \qquad \forall i \in I \tag{3.8}$$

$$\sum_{j \in J} a_{ij}^{B} \geq PL_i \qquad \forall i \in I \tag{3.9}$$

$$\sum_{i \in I} a_{ij}^{P} - \sum_{k \in K} b_{jk}^{P} = 0 \qquad \forall j \in J \tag{3.10}$$

$$\sum_{i \in I} a_{ij}^{B} - \sum_{k \in K} b_{jk}^{B} = 0 \qquad \forall j \in J \tag{3.11}$$

$$\sum_{j \in J} b_{jk}^{P} = d_k \qquad \forall k \in K \tag{3.12}$$

$$\sum_{j \in J} b_{jk}^{B} = d_k \qquad \forall k \in K \tag{3.13}$$

$$x_j^{R} \in \{0,1\} \qquad \forall j \in J \tag{3.14}$$

$$x_j^{U} \in \{0,1\} \qquad \forall j \in J \tag{3.15}$$

$$a_{ij}^{P} \geq 0 \qquad \forall i \in I, \forall j \in J \tag{3.16}$$

$$a_{ij}^{B} \geq 0 \qquad \forall i \in I, \forall j \in J \tag{3.17}$$

$$b_{jk}^{P} \geq 0 \qquad \forall i \in I, \forall j \in J \tag{3.18}$$

$$b_{jk}^{B} \geq 0 \qquad \forall i \in I, \forall j \in J \tag{3.19}$$

Equation (3.2) states that either of RRS or URS can be open, but not both. Equation (3.3) states that the model required locating at least one RRS. Equations (3.4) and (3.5) are capacity constraint for RS as primary and backup assignment, respectively. Equations (3.6) and (3.7) are upper bounds for available supply as primary and backup assignment, respectively. Equations (3.8) and (3.9) are lower bounds for available supply as primary and backup assignment, respectively. Equations (3.10) and (3.11) are balances of product flow as primary and backup assignment, respectively. Equations (3.12) and (3.13) mean demand of every customer must be satisfied as primary and backup assignment, respectively, Equations (3.14) and (3.15) are integrality restrictions on decision variables. Equations (3.16) - (3.19) are nonnegative constraints for primary and backup assignment amounts.

3.2.2 Multi-single allocation model (MSA Model)

In this model, we consider each RS will receive the product from multiple DCs while customer only from one RS. The model for MSA is described as follows:

Minimize

$$\sum_{j\in J} F_j^U x_j^U + \sum_{j\in J} F_j^R x_j^R$$

$$+\sum_{j\in J}(1-q_j)\left(\sum_{i\in I}(C_i^P + T1_{ij}^P)a_{ij}^P + \sum_{k\in K}(H_j^P + T2_{jk}^P)d_k y_{jk}^P\right)$$

$$+\sum_{j\in J} q_j\left(\sum_{i\in I}(C_i^B + T1_{ij}^B)a_{ij}^B + \sum_{k\in K}(H_j^B + T2_{jk}^B)d_k y_{jk}^B\right) \qquad (3.20)$$

Subject to:

(3.2) - (3.9) and (3.14) - (3.17)

$$\sum_{j\in J} y_{jk}^P = 1 \qquad \forall k \in K \qquad (3.21)$$

$$\sum_{j\in J} y_{jk}^B = 1 \qquad \forall k \in K \qquad (3.22)$$

$$y_{jk}^P \le x_j^U + x_j^R \qquad \forall j \in J, \forall k \in K \qquad (3.23)$$

$$y_{jk}^{B} \leq x_{j}^{R} \qquad \forall j \in J, \forall k \in K \tag{3.24}$$

$$\sum_{i \in I} a_{ij}^{P} - \sum_{k \in K} d_k y_{jk}^{P} = 0 \qquad \forall j \in J \tag{3.25}$$

$$\sum_{i \in I} a_{ij}^{B} - \sum_{k \in K} d_k y_{jk}^{B} = 0 \qquad \forall j \in J \tag{3.26}$$

$$y_{jk}^{P} \in \{0,1\} \qquad \forall j \in J, \forall k \in K \tag{3.27}$$

$$y_{jk}^{B} \in \{0,1\} \qquad \forall j \in J, \forall k \in K \tag{3.28}$$

In MSA model the explanation of the objective function and constraints are all equal to the MMA model except for equations (3.21) and (3.22). These equations express that each customer must be assigned to single RS both for the primary and backup assignment, respectively.

3.2.3 Single-single allocation model (SSA Model)

In this model, we consider each RS can receive just from single DC and customer also receives from single RS. The model for SSA is described as follows:

$$\sum_{j\in J} F_j^U x_j^U + \sum_{j\in J} F_j^R x_j^R$$

$$+\sum_{j\in J}(1-q_j)\left(\sum_{i\in I}(C_i^P + T1_{ij}^P)a_{ij}^P z_{ij}^P + \sum_{k\in K}(H_j^P + T2_{jk}^P)d_k y_{jk}^P\right)$$

$$+\sum_{j\in J} q_j\left(\sum_{i\in I}(C_i^B + T1_{ij}^B)a_{ij}^B z_{ij}^B + \sum_{k\in K}(H_j^B + T2_{jk}^B)d_k y_{jk}^B\right) \qquad (3.29)$$

Subject to:

(3.2) - (3.3), (3.14) - (3.17), (3.21) - (3.24) and (3.27) - (3.28)

$$\sum_{i\in I} z_{ij}^P = 1 \qquad \forall j \in J \qquad (3.30)$$

$$\sum_{i\in I} z_{ij}^B = 1 \qquad \forall j \in J \qquad (3.31)$$

$$\sum_{i\in I} a_{ij}^P z_{ij}^P \le U_j (x_j^U + x_j^R) \qquad \forall j \in J \qquad (3.32)$$

$$\sum_{i\in I} a_{ij}^B z_{ij}^B \le U_j x_j^R \qquad \forall j \in J \qquad (3.33)$$

$$\sum_{j \in J} a_{ij}^{P} z_{ij}^{P} \leq PU_i \qquad \forall i \in I \tag{3.34}$$

$$\sum_{j \in J} a_{ij}^{B} z_{ij}^{B} \leq PU_i \qquad \forall i \in I \tag{3.35}$$

$$\sum_{j \in J} a_{ij}^{P} z_{ij}^{P} \geq PL_i \qquad \forall i \in I \tag{3.36}$$

$$\sum_{j \in J} a_{ij}^{B} z_{ij}^{B} \geq PL_i \qquad \forall i \in I \tag{3.37}$$

$$\sum_{i \in I} a_{ij}^{P} z_{ij}^{P} - \sum_{k \in K} d_k y_{jk}^{P} = 0 \qquad \forall j \in J \tag{3.38}$$

$$\sum_{i \in I} a_{ij}^{B} z_{ij}^{B} - \sum_{k \in K} d_k y_{jk}^{B} = 0 \qquad \forall j \in J \tag{3.39}$$

$$z_{ij}^{P} \in \{0,1\} \qquad \forall i \in I, \forall j \in J \tag{3.40}$$

$$z_{ij}^{B} \in \{0,1\} \qquad \forall i \in I, \forall j \in J \tag{3.41}$$

In this model, equations (3.29), (3.32) – (3.39) are known to be non-linear. To linearize the terms like $a_{ij}^{P} z_{ij}^{P}$ and $a_{ij}^{B} z_{ij}^{B}$, we introduced new variables and the additional constraints as follows:

$$Z_{ij}^{P} = a_{ij}^{P} z_{ij}^{P} \tag{3.42}$$

$$Z_{ij}^{B} = a_{ij}^{B} z_{ij}^{B} \tag{3.43}$$

$$a_{ij}^{P} - Z_{ij}^{P} \geq 0 \qquad \forall i \in I, \forall j \in J \tag{3.44}$$

$$a_{ij}^{B} - Z_{ij}^{B} \geq 0 \qquad \forall i \in I, \forall j \in J \tag{3.45}$$

$$a_{ij}^{P} - B \leq Z_{ij}^{P} - Bz_{ij}^{P} \qquad \forall i \in I, \forall j \in J \tag{3.46}$$

$$a_{ij}^{B} - B \leq Z_{ij}^{B} - Bz_{ij}^{B} \qquad \forall i \in I, \forall j \in J \tag{3.47}$$

B is large value

3.3 Numerical Experiment

In this section, we show the result of numerical experiment. In practice, we solved the formulated problems using commercial software known as CPLEX 12.2 on a computer with 2.66GHz core 2 duo processor and 2 GB of RAM. These instances consist of 2 DCs, 5 candidate RSs and 50 customers (Hereinafter, such a feature will denoted as (2-5-50).

The probability of disruption q_j is assumed to be the same for $\forall j \in J$ (Hereinafter, denote just as q). We assume q as 0.01 for the safe condition and as 0.1, 0.2, 0.3, 0.4, 0.5, for risky situations. The fixed cost for opening RRS F_j^R requires by two times of URS F_j^U. Every node denoting the members of the facilities is generated randomly. The distance between them was calculated on a basis of Euclidian norm. Then, we get the unit transportation cost by multiplying the unit factor 1.5 and 1.0 with the distance between DC to RS and RS to customer, respectively. Every backup costs is set to 1.5 times from the normal values.

In Table 3.1, we compare the problem sizes among MMA, MSA and SSA model in terms of system parameters to evaluate the computation time.

Table 3.1: Number of decision variables and constraints

Model	Real variable number	0-1 variable number	Constraint number
MMA	520	10	134
MSA	520	510	634
SSA*	520	530	816

*before linearization

3.3.1 In the case of MMA model

Results of MMA model are illustrated in Figures 3.4 and 3.5. We also showed it in Table 3.2 to compare the results among the model. From these, we know the DCs will distribute product to three open RSs for probability of disruption (q_j) 0.01, 0.1, 0.2, 0.3 and 0.5 (RS#2, RS#4 and RS#5) in a multiple distribution manner. Except for q=0.4, two reliable RSs exist in the system. RS#4, which previously is unreliable RS, is eliminated in this probability. RS#4 turns to reliable ones when we increase the probability to 0.5.

In Figure 3.5 where q=0.5, all customers are assigned to RRS due to the increased probability of disruption. Though the opening RSs are same as the foregoing one, members of RS is different, and the distribution manner is considerably different with each other.

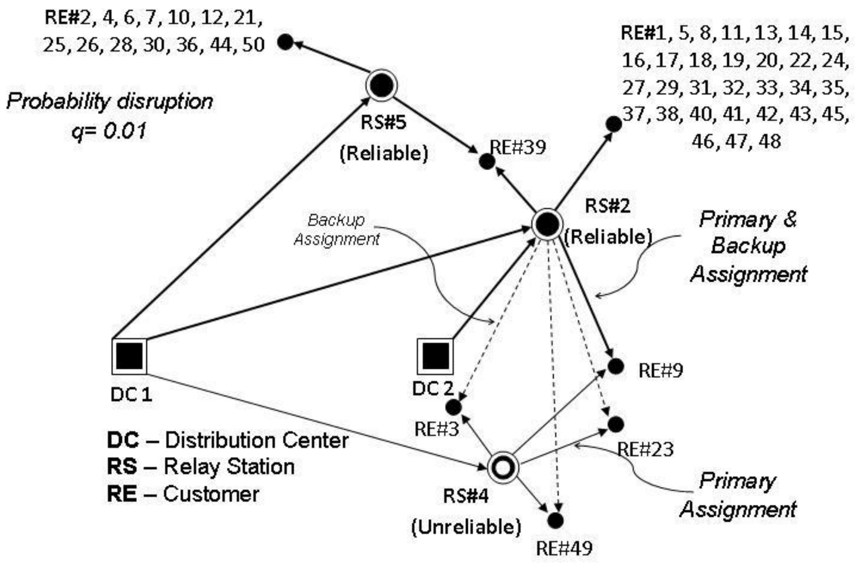


Figure 3.4: MMA model with disruption probability 0.01

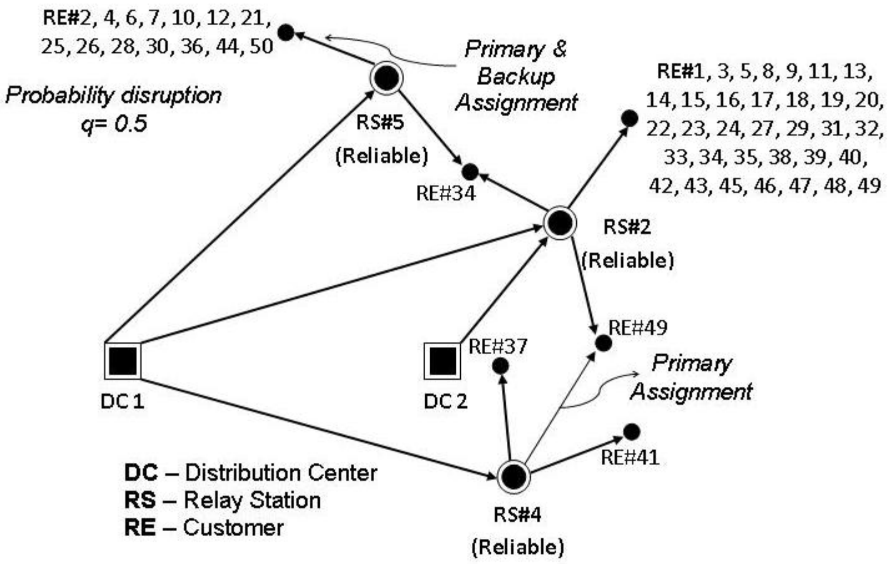


Figure 3.5: MMA model with disruption probability 0.5

Moreover, it is interesting to see that RS#4 is used as the unreliable RS when *q* is low while it is as the reliable one at the higher *q* after it disappears during the middle range of probability. This is because the opening cost of RS#4 is quite cheap among RSs. Hence, opening this RS as URS can save the transportation cost greatly when *q* is low. In contrast, when *q* becomes higher, it makes sense to open this RS as RRS to cope with the disruption as well as transportation cost saving. The situation when *q*=0.4 appears as the transient status of these two cases. This fact can confirm the adequateness of the proposed model.

3.3.2 In the case of MSA model

In this model, customers force to receive the product only from one RS. This requirement will bring about the increase in the normal cost of the model, where customers have no choice to receive the product from another RS. The results of the MSA model are illustrated in Figures 3.6 and 3.7.

We obtained the same result as MMA model regarding the number of open RSs. The expected cost is slightly higher than the MMA model due to the single assignment of customer to RS. The complete results of this model for each probability of disruption are shown in Table 3.2.

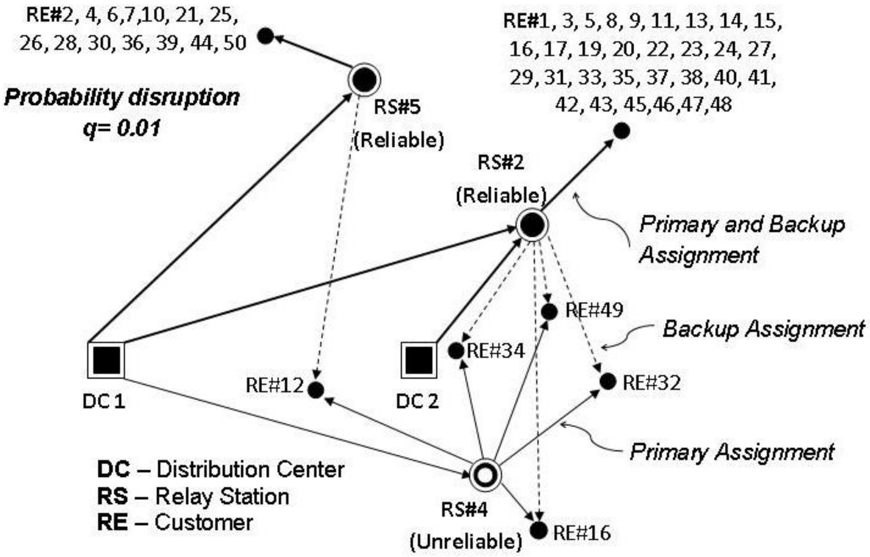


Figure 3.6: MSA model with disruption probability 0.01

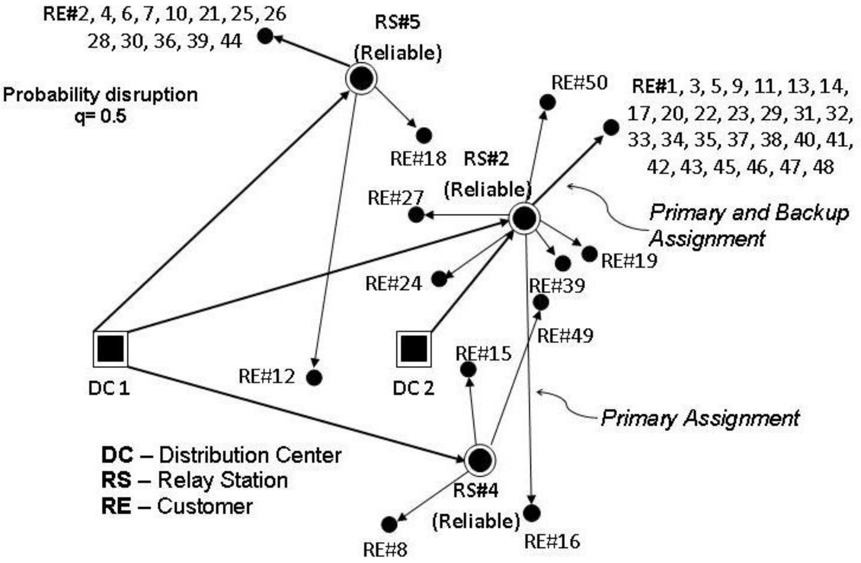


Figure 3.7: MSA model with disruption probability 0.5

3.3.3 In the case of SSA model

SSA model is originally a non-linear model. After the linearization shown already, the SSA model is easily solved. The result of the SSA model for probability 0.01 is depicted in Figure 3.8 and the summary is shown in Table 3.2.

All open RSs are reliable ones over the disruption probabilities, and the configuration become simple.

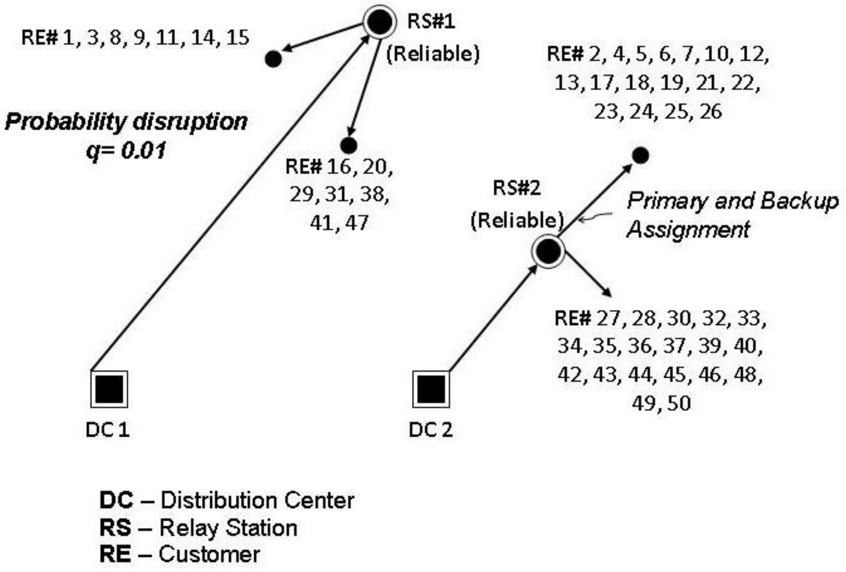


Figure 3.8: SSA model with disruption probability 0.01

3.4 Comparison of Results

In Table 3.2, we summarize the computation result for three types of allocation models. These are all global optimal solutions (gap is 0.0). There are four types of costs are shown in the table, the fixed cost, normal cost, abnormal cost, and expected cost. As supposed a priori, we obtained the results such that MMA is best, MSA follows it and SSA worst over all probability disruption. This is because MMA model is most flexible and SSA least compared with the other models. However if we are required to evaluate the simplicity of the network design, SSA becomes best. This means there is a trade-off between the cost and the configuration to make a final decision. In our knowledge, such idea has never been addressed.

The comparison of CPU to obtain the optimal solution times of each model is also shown in Table 3.2. As can be observed thereat, number of binary variables and constraints has a strong impact on the CPU time.

Table 3.2 Summary of the case solution for MMA, MSA and SSA model

Probability (*q*)		**0.01**		**0.1**		**0.2**		**0.3**		**0.4**		**0.5**	
Components		**URS**	**RRS**	**URS**	**RRS**	**URS**	**RRS**	**URS**	**RRS**	**URS**	**RRS**	**URS**	**RRS**
Number of Facilities (RS #)	MMA	1 (#4)	2 (#2,5)	1 (#4)	2 (#2,5)	1 (#4)	2 (#2,5)	1 (#4)	2 (#2,5)	0	2 (#2,5)	0	3 (#2,4,5)
	MSA	1 (#4)	2 (#2,5)	1 (#4)	2 (#2,5)	1 (#4)	2 (#2,5)	1 (#4)	2 (#2,5)	0	2 (#2,5)	0	3 (#2,4,5)
	SSA	0	2 (#1,2)	0	2 (#1,2)	0	2 (#1,2)	0	2 (#1,2)	0	2 (#1,2)	0	2 (#1,2)
Fixed Cost (*x 1000)*	MMA	18	270	18	270	18	270	18	270	0	270	0	306
	MSA	18	270	18	270	18	270	18	270	0	270	0	306
	SSA	0	306	0	306	0	306	0	306	0	306	0	306
Normal Cost	MMA	4,145,000		4,145,000		4,145,000		4,145,000		4,174,250		4,145,000	
	MSA	4,145,200		4,145,675		4,145,525		4,145,200		4,174,925		4,145,675	
	SSA	4,833,900		4,833,900		4,833,900		4,833,900		4,833,900		4,833,900	
Abnormal Cost	MMA	6,255,565		6,255,565		6,255,565		6,255,565		6,255,565		6,211,915	
	MSA	6,257,285		6,255,865		6,255,865		6,257,065		6,255,865		6,211,215	
	SSA	7,244,940		7,244,940		7,244,940		7,244,940		7,244,940		7,244,940	
Expected Cost	MMA	4,454,105		4,644,056		4,855,113		5,066,169		5,276,776		5,484,457	
	MSA	4,454,320		4,644,694		4,855,593		5,066,759		5,277,301		5,484,945	
	SSA	5,164,010		5,381,004		5,622,108		5,863,212		6,104,316		6,345,420	
CPU time (s)	MMA	0.01		0.03		0.03		0.03		0.01		0.03	
	MSA	0.23		0.28		0.20		0.16		0.14		0.20	
	SSA	0.06		0.08		0.06		0.06		0.06		0.06	
Gap (%)	MMA	0.00		0.00		0.00		0.00		0.00		0.00	
	MSA	0.00		0.01		0.01		0.01		0.01		0.01	
	SSA	0.00		0.00		0.00		0.00		0.00		0.00	

URS: unreliable relay station RRS: reliable relay station

3.5 Larger Data Experiments

Four sets of data problems were constructed to conduct the experiment with larger data size. In this research, the numerical experiment conducted in order to compare the performance of MMA, MSA and SSA models in the presence of disruption risk. Through numerical experiment, we can analyze which model will provide the best performance among them using the same data and parameters. Unfortunately, the MIP solver (CPLEX) cannot solve larger data for SSA model because infeasible reason. This infeasibility results due to the capacity constraint of relay station.

Figures 3.9 and 3.10 clearly show the expected cost with different model (MMA and MSA) for each disruption probabilities. With the increased of disruption probabilities, the expected cost for each model MMA and MSA are increased linearly. It is straightforward to see that the performance for the MMA model to outperform the MSA model compare to the total expected cost. The expected cost for MSA is slightly higher than MMA for the same data set. In average difference between the expected costs of MMA and MSA is around 0.48%. This means that the decision to apply between MMA model and MSA model not significantly influenced by the expected total cost. Table 3.3 summarizes the result of numerical experiment for MMA and MSA model with data set 5-20-200.

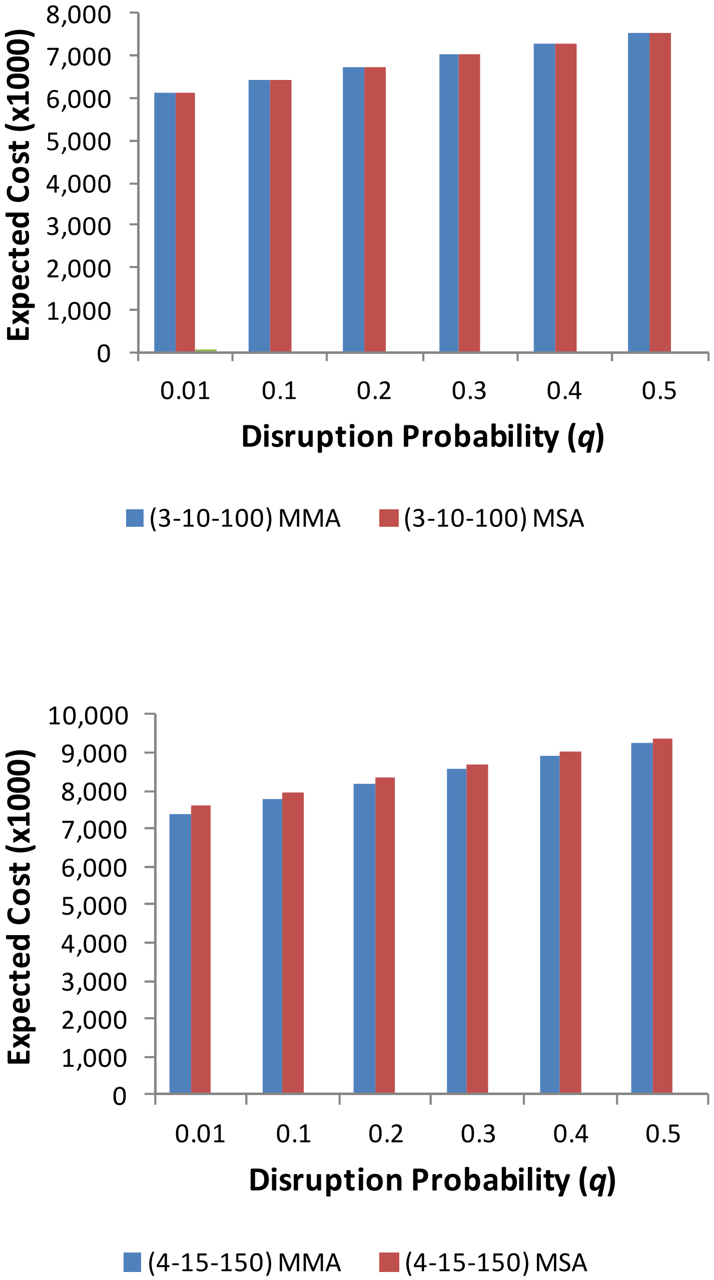


Figure 3.9: The Expected cost under various model (MMA and MSA) and disruption probabilities for data size (3-10-100) and (4-15-150)

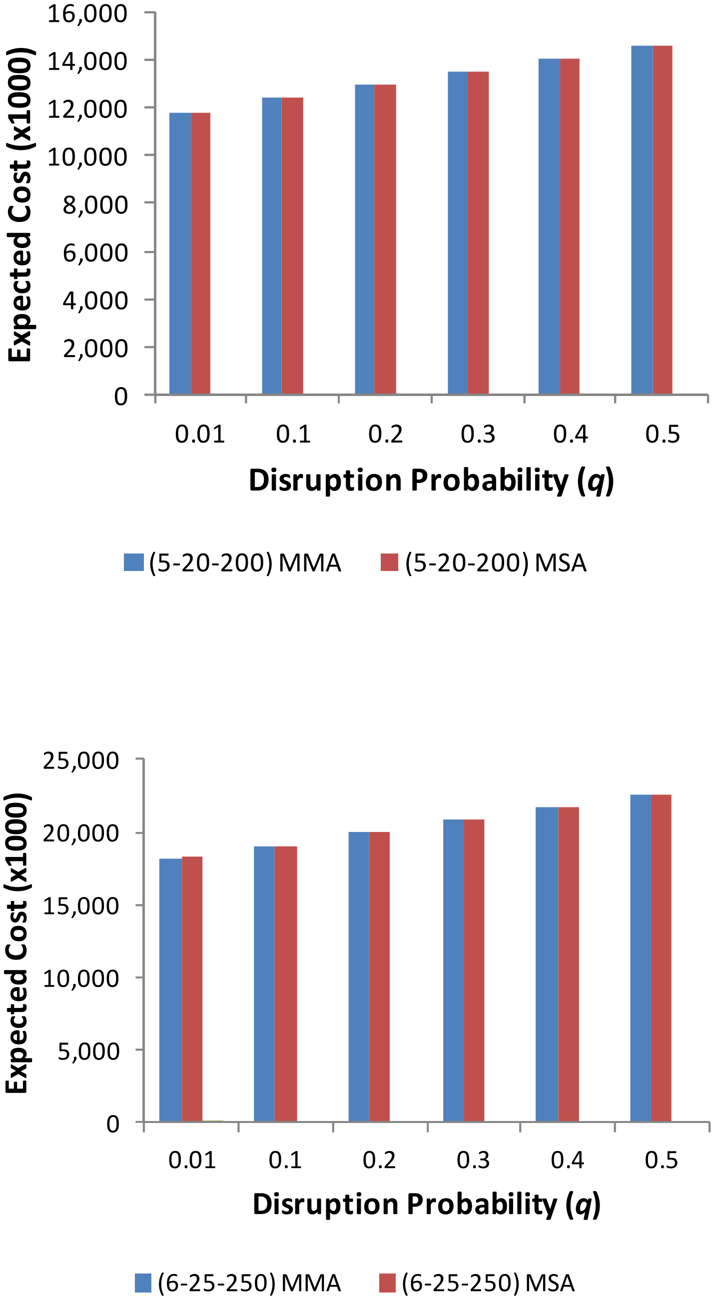


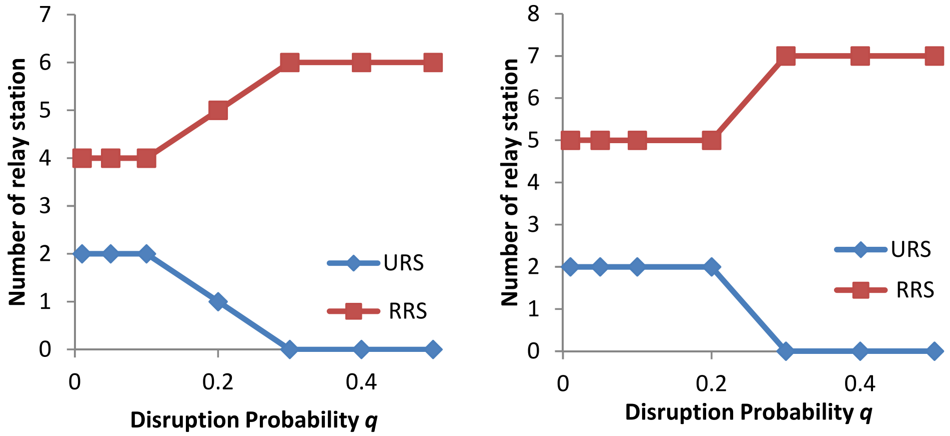
Figure 3.10: The Expected cost under various model (MMA and MSA) and disruption probabilities for data size (5-20-200) and (6-25-250)

From Table 3.3, we confirmed the maximum open reliable relay station (RRS) of each disruption probabilities for data set 5-20-200. In a safe condition, when a disruption probability is low, it is optimal to build both types of relay station, URS and RRS. In this situation, demand of the customer will be fulfill from both types of relay station. The operational cost of logistic network is cheaper by providing a combination between primary and backup in term of operational cost such as transportation cost and handling cost in relay station. In safe condition, most of allocation flow as a normal state which is cheaper than abnormal state. In contrast, in risky condition, when disruption probability is high then allocation change to abnormal state which is more expensive due to backup reason.

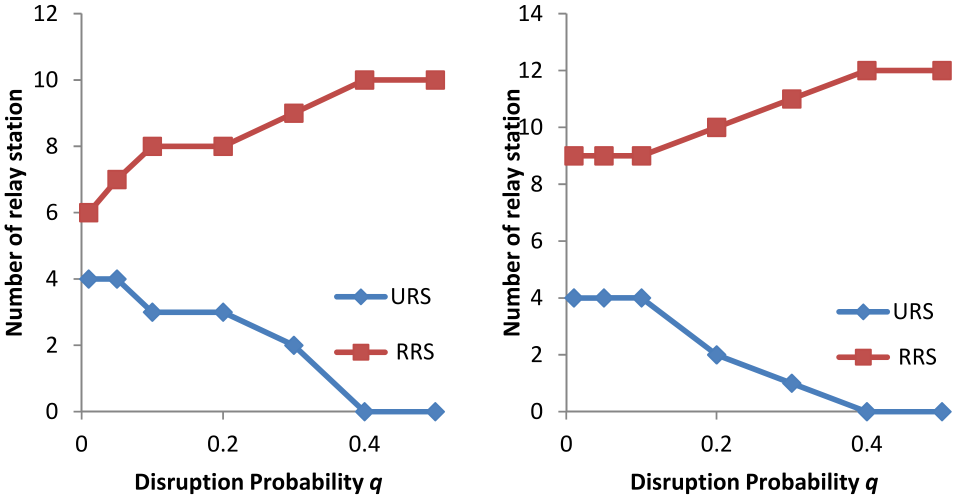
Table 3.3 Summary of the case solution for MMA, MSA with data set 5-20-200

Model Data Set	***q***	**URS**		**RRS**		**Fixed Cost**		**Normal Cost (a)**	**Abnormal Cost (b)**	**Expected Cost**	**CPU time (Sec)**	**Gap %**
		Qty	**No.**	**Qty**	**No.**	**URS**	**RRS**					
(5-20-200) MMA	**0.01**	4	#1,9,11,17	6	#2,4,8,12,13,14	250,100	1,002,200	10,474,625	18,614,840	11,808,327	1.27	0.38
	0.05	4	#9,10,11,17	7	#1,2,4,8,12,13,16	228,900	1,105,400	10,422,875	16,759,585	12,074,011	1.69	0.31
	0.1	3	#10,11,16	8	#1,2,4,8,9,12,13,17	171,900	1,219,400	10,422,875	16,165,655	12,388,453	1.19	0.49
	0.2	3	#10,11,16	8	#1,2,4,8,9,12,13,17	171,900	1,219,400	10,422,875	16,165,655	12,962,731	0.63	0.00
	0.3	2	#10,16	9	#1,2,4,8,9,11,12,13,17	117,900	1,327,400	10,422,875	15,917,755	13,516,639	0.91	0.70
	0.4	0	0	10	#1,2,4,8,9,10,11,12,13,17	0	1,438,000	10,515,625	15,756,215	14,049,861	0.80	0.00
	0.5	0	0	10	#1,2,4,8,9,10,11,12,13,17	0	1,438,000	10,515,625	15,756,215	14,573,920	0.77	0.38
(5-20-200) MSA	**0.01**	4	#1,9,11,17	6	#2,4,8,12,13,14	250,100	1,002,200	10,477,325	18,624,530	11,811,097	147.11	0.01
	0.05	4	#9,10,11,17	7	#1,2,4,8,12,13,16	228,900	1,105,400	10,426,175	16,761,610	12,077,247	176.98	0.01
	0.1	3	#10,11,16	8	#1,2,4,8,9,12,13,17	171,900	1,219,400	10,425,850	16,168,805	12,391,445	194.91	0.01
	0.2	3	#10,11,16	8	#1,2,4,8,9,12,13,17	171,900	1,219,400	10,426,575	16,167,830	12,966,126	253.69	0.01
	0.3	2	#10,16	9	#1,2,4,8,9,11,12,13,17	117,900	1,327,400	10,426,700	15,921,205	13,520,352	259.44	0.01
	0.4	0	0	10	#1,2,4,8,9,10,11,12,13,17	0	1,438,000	10,518,875	15,761,390	14,053,881	262.73	0.01
	0.5	0	0	10	#1,2,4,8,9,10,11,12,13,17	0	1,438,000	10,519,075	15,761,240	14,578,158	419.77	0.01

Figure 3.11 illustrate the number of open relay station for each disruption probabilities with different data set.



(a) data set 3-10-100 (b) data set 4-15-150



(c) data set 5-20-200 (d) data set 6-25-250

Figure 3.11:Number of open relay station for each disruption probabilities *q*

3.6 Sensitivity Analysis

Sensitivity analysis is performed in order to understand the effect of changes two parameters namely disruption probability q and opening cost ratio r (F_j^U / F_j^R) between URS and RRS. By keeping the value of F_j^U is constant and F_j^R is vary depend on opening cost ratio r. We assume that value of r is varying from 1.05 to 3.00. If value of r is small than this means that RRS is cheaper to build. In our previous experiment we define that r = 2, which mean opening RRS cost twice compared to URS. Disruption probability q is assumed vary from 0.01 to 0.5. For this analysis we prepared data from MMA model with data set 5-20-200.

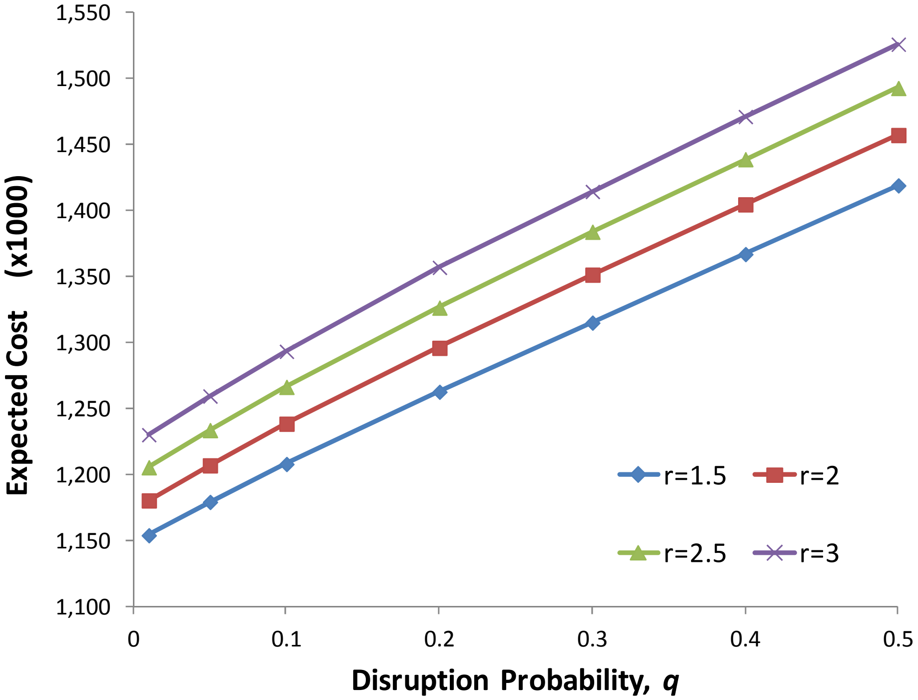


Figure 3.12: Sensitivity analysis of q and r – MMA model with data set (5-20-200)

Figure 3.12 illustrates the result obtained with the corresponding disruption probability q and opening cost ratio r. Notice that the expected cost increases as q and r increase. In the risky situation, when disruption probability is high then number of RRS is increased. The increasing of expected cost in risky condition is influenced by the total number of open RRS and total backup cost due to the abnormal condition.

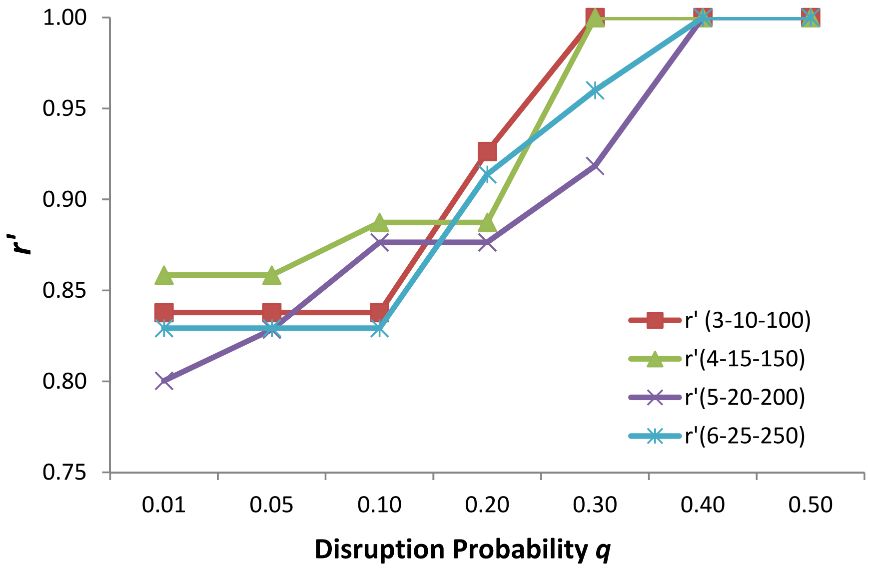
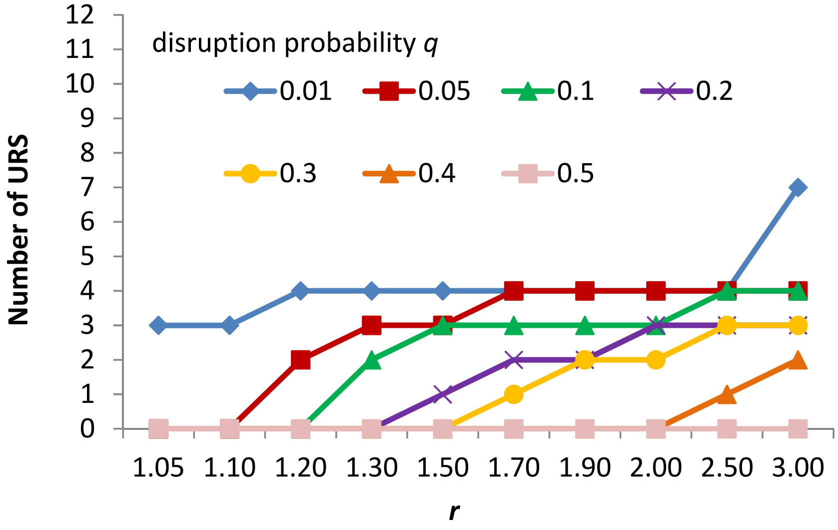


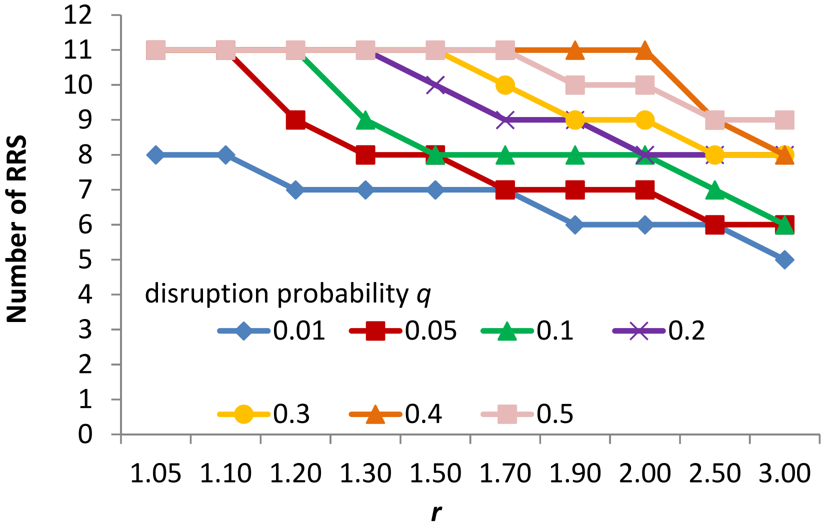
Figure 3.13: Sensitivity analysis of q and r’

In Figure 3.13 shows the relationship between q and r’. We define $r' = F^R/(F^R + F^U)$, as a ratio opening cost of RRS to the total opening cost. This sensitivity analyses suggest that the decision to open RRS is more appropriate than URS when the disruption probability increase.

Figure 3.14 depicts the relationship between numbers of opening facilities URS and RRS and the relationship with the opening cost ratio *r*. This sensitivity analysis is carried out to observe how the disruption probability *q* and *r* affect the optimal number of URS and RRS. Number of URS increases with the increasing value of the opening cost ratio *r* for all disruption probability *q*. Therefore, we can say that the number of RRS is reduced when the opening cost RRS is getting more expensive. Furthermore, the result revealed that as the value disruption probability q=0.5 or in risky situation, there is no URS facility open even though the difference of the opening cost between URS and RRS is small.



(a) Number of URS – r



(b) Number of RRS – r

Figure 3.14 Sensitivity analysis of q and r

3.7 Conclusion

In this chapter, we presented the comparison result of three allocation models, multi-multi allocation (MMA), multi-single allocation (MSA) and single-single allocation (SSA) model, in multistage logistic network design considering disruption risk. We formulate each model as mixed-integer programming problem and use commercial optimization software to solve the model. Through the numerical experiment, we have shown each model is promising to design the multi stage logistic networks available for the mitigation planning. Additionally, we have conducted a sensitivity analysis in order to understand the effect of changes parameters (*q, r, r'*) to the total expected cost and the optimal number of open relay station.

Future studies should be devoted to evaluate the solution ability of the commercial software, and apply the models to some real world applications.

Chapter 4

MORPHOLOGICAL ANALYSIS

4.1 Introduction

In the last decade, supply chains are faced with a rising complexity of structures, processes and products. An attention to the supply chain network design considering disruption risk also increasingly to attracted due to globalization. The globalization is strengthening the complexity including, shortened product lifecycles and customer demands. An efficient and robust supply chain networks leads to sustainable competitive advantage for the company and helps to cope with the increasing environmental disruption and uncertainties. Configuration of the logistic network is one of the most important and strategic issue in the supply chain network design that has long lasted effect on the performance of the supply chain. One example is determining the number and location of the facility and also types of allocation model.

The strategic configuration of the supply chain is a key factor affecting the efficient operations of supply chain and involving large capital investment resources in the long term makes the supply chain network design problem is important (Santoso 2005). The problem with complexity becomes a significant cost driver within a supply chain and also contributes to variability and uncertainty. One powerful way to overcome the complexity is through creating a higher level of adaptability in the supply chain. An adaptable supply chain is one that can change the structure in response to fundamental changes in the business environment. The emphasis in an adaptable supply chain is very much on reconfiguration and flexibility.

The earliest mention of supply chain complexity in the academic literature appears to be by Wilding (1998), who proposed a supply chain complexity triangle, comprised of what the author calls deterministic chaos, parallel interactions and demand amplification. The effects of a raised complexity in supply chains are manifold. The impacts of the complexity such as rising costs, enlarging efforts for indirect operations and increasing forecast uncertainties. Bozarth *et al.* (2009) showed the result that upstream complexity, downstream complexity and internal manufacturing complexity have a negative performance impact on manufacturing plant. The strong relation between complexity and efficiency in supply chain management becomes an important challenge of today's business management.

Another concept related to flexibility design of the model besides complexity is simplicity. The concepts of simplicity were clearly defined in the empirical study by Collins *et al*. (1998). Simplicity was about streamlining material flow processes and reduction in operations complexity.

In the real world applications, the concept of simplicity and complexity has been used by the companies depend on the goals to be achieved. One example related to the simplicity implementation is Toyota Company decided to implement JIT (*Just in Time*) concept in its operation. JIT strategy encourages the two partners to streamline the supply chain process and encourage the buyer supplier relationship to a single sourcing model by reducing the number of supplier. The main objective of supplier reduction is to build stronger and longer term relationships with suppliers and also reducing the fixed costs that incurred by multiple supplier relationships. However, single sourcing also exposed to greater risk of supply chain interruption. Toyota

Brake valve crisis in 1997 exemplifies the possibility occurrence of supply chain disruption as a result of single sourcing in a JIT system (Yu *et al.* 2009).

One example of implementation complexity in the supply chain network design is the decision to use multiple sources of products supply. Multiple sourcing is the condition where buyer (customer) can receive product from more than one supplier. Yu *et al.* (2009) make the definition of multiple sourcing as a buyer does business with several suppliers and plays one supplier against the other to enjoy the best price advantage. Multiple sourcing is often referred as a possible solution to protect against disruption in supply. However, nowadays most firms have made a lot of efforts to reduce their supplier base and some of them may be a little reluctant to adopt the multiple sourcing approaches. Some companies still applied this concept by reason of develop multiple supply sources for the same product that will cost effectively enhance the flexibility. For example, Hewlett-Packard applied new procurement strategy, first it relies on a supplier for a fixed quantity the calls on second supplier for flexible quantities.

In this study, we proposed new metrics to measure the performance the complexity of the multi stage logistic networks considering disruption risk and present three different types of allocation model each of which will present, in parallel, the respective backup design and operational aspects associated with the design. Consequently, the aim of this study is to evaluate the properties of these models including the interests in the morphological aspect that is essential for resilient system development, but hard to capture explicitly in practice. This is a novel approach to cope with decision making in an ill-posed environment.

4.2 Business Continuity Management / Plan

In today’s world situation, risk and globalization become a critical issue in the industrial field. Business has far more economic interdependency between regions than ever before. Some industry rely on longer supply chain for physical production of the product and facing increasingly uncertain demand as well as supply and also probability being disrupted in facility. Every organization needs a business continuity management/plan to reduce potential risks and ensure the continuity of important business processes after the event of disruption.

Business Continuity Institute (BCI) a definition of what Business Continuity management actually is, and this definition has provided the foundation on which the Institute developed its approach to standards, education, and individual development. The definition stated that Business continuity management is a holistic management process that identifies potential threats to an organization and the impact to business operations that those threats, if realized, might cause, and which provides a framework for building organizational resilience with the capability for and effective response that safeguards the interests of its key stakeholders, reputation, brand and value creating activities (Hiles, A. *Ed* (2011).

Another definition of Business continuity management (BCM) is defined as the development of strategies, plans and actions which provide protection or alternative modes of operation for those activities or business processes which, if they were to be interrupted, might otherwise bring about a seriously damaging or potentially fatal loss to the enterprise (Hiles and Barnes 2010). Developing action plans is important in BCM, and business continuity planning (BCP) is a term often used. BCP is planning to ensure continued operations in case of a catastrophic event.

In today's The issue of risk handling and risk sharing along the supply chain is an important topic in industrial field, especially those industries moving towards longer supply chains and facing increasingly uncertain demand as well as supply and also probability being disrupted in facility. Risk sources are the environmental, organizational or supply chain related variables that cannot be predicted with certainty and that affect the supply chain-outcome variables. Jüttner (2003) suggest organizing risk sources relevant for supply chains into three categories:

(1) Numbers: external to the supply chain.
(2) Internal to the supply chain.
(3) Network related.

Pfleeger (2000) define the definition of risk management as a technique to understand the risk and control or minimize the impact of the risk. A risk is an unwanted event that has negative consequences. Parallel to risk management is the issue of how mitigating the consequences of a disruption and dealing how to minimize the business impact. This is normally referred to as business continuity management (BCM) and relates to process management and techniques to provide continuous operations.

According to the increase in various risks, American and European countries have started with establishing an institute as a countermeasure for the unexpected disruption. BCM is an inclusive idea of BCP and defines as a holistic management process that identifies potential impacts that threaten an organization and provides a framework for building resilience with the capability for an effective response for recovery or continuity in the event of the disaster. Meanwhile, BCP is a dealing which identifies the organization's exposure to internal and external threats and to provide effective prevention and recovery for the organization while maintaining competitive advantage and value system integrity.

In Japan, setting off by some semiconductor enterprises in 2003, this activity is now undertaking gradually for many industries. Especially, after the recent crucial disaster in eastern Japan and Thailand, it seems that the importance of such movement will be overwhelming all over the manufacturing. The basic idea of BCP is illustrated as Figure 4.1(Cabinet office 2005). Eventually, the aim of this plan is to reduce RTO (Required Time Objective) as short as possible. In other words, it must involve a preventive and remediable plan against emergency for management and/or decision making to maintain the business continuously.

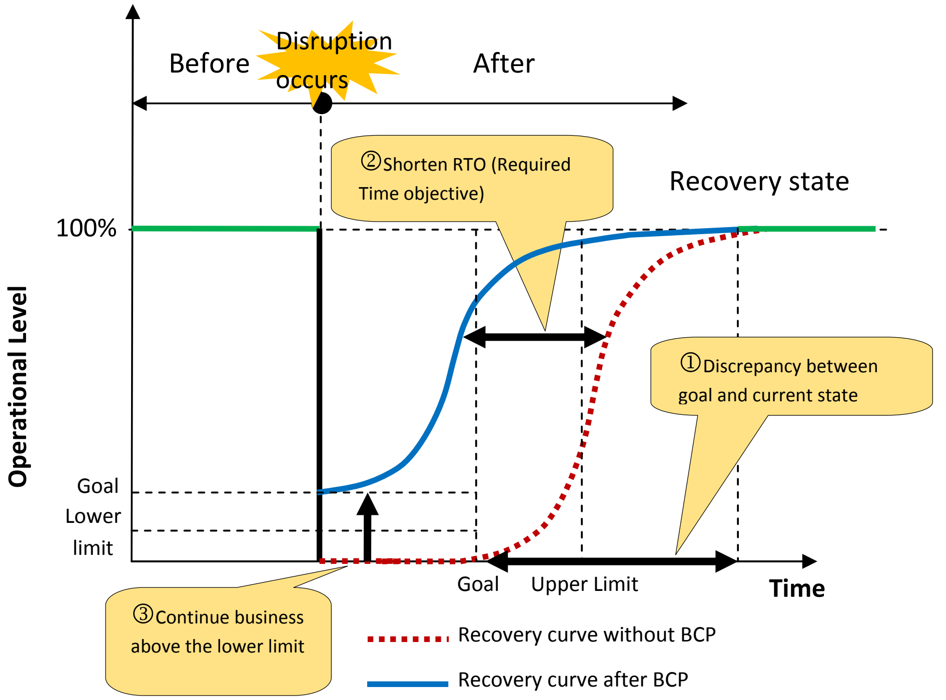


Figure 4.1: An essence of BCP concept

4.3 Morphological analysis

Among the sources of risk within a supply chain, the risk in demand side is shown to have greater impact and higher likelihood of occurrence (Kersten *et al*. 2006). In addition, three echelon logistics are popular (Shimizu *et al*. 2008) and more flexible compared with the two echelon logistics. In this study, therefore, we will pay an attention to the demand side and take three echelon problems which are consisted of distribution center (DC), relay station (RS) and customer (RE).

Having proper backup facilities is an essential dealing to reduce RTO in BCP and to create a resiliency mentioned in section 4.2. Then, this study tries to present a resilient network from sound DCs to customers via RSs potentially affected by the incident. Generally speaking, since every RS locates near to customer site than DC, it is adequate to consider decision problem at RS level. As RS, we provide two kinds of RS, i.e., reliable RS (RRS) and unreliable RS (URS). URS is no longer available for serving customers when RS fails or disruption would occur. This means the alternative sources of supply become necessary to provide service to the customers. On the other hand, RRS is the hardened ones which have additional capacity and/or external alternative sourcing strategy for examples. So it can continue the business even after the incident but it costs more to manage such facilities.

A major interest to consider these three structures is to emphasize the importance of the intangible factor that may be associated with the flexibility, service, resiliency, etc. Though those are important aspects in practical decision making, it is difficult to give certain evaluation metrics for them. In fact, any studies have not addressed such idea in terms of the multiple models. As a preliminary study to compactly account such factors, we take into account the numbers of paths necessary to that constitute the networks both at normal and abnormal situations. As supposed naturally, increase in this number will raise complexity and impose additional loads for every member of the logistic network.

Noticing the correlation of the risk drivers hidden in wide societal and human activities, we know it is insufficient just to consider the economical aspect. Hence, this study tries to consider a morphological structure of the network to evaluate certain intangible factors behind the cost. For this purpose, we take three models, i.e., multi-multi allocation (MMA), multi-single allocation (MSA) and single-single allocation (SSA) mode for the consideration. In MMA model, each RS will receive the product from multiple DCs and each customer also from multiple RSs. In MSA model, each RS can receive the product from multiple DCs while customer only from single RS. Finally, in SSA model, each RS receives just from single DC and customer also receives from single RS.

We formulate each model as a mixed-integer programming problem. The objective function is expected costs that consist of shipping cost at DC, transportation cost between each RS and handling cost at RS besides the fixed cost for opening RS. Among the decision variables, the binary variables closely relate with the structure of the network (design), while the integer variables do with the operations under the prescribed structure. In other word, the resulting different structure will return the corresponding different operations.

Since we can derive the different network configurations, it makes sense to evaluate such feature depending on the models. They are representatively characterized by the numbers of path both at the normal and the abnormal states. Then we try to use the number of multiple distributions both from DCs to RSs and from RSs to customers as a surrogate for evaluating a certain factor associated with morphological structure. Receiving products from different multiple suppliers will increase the tedious treatments and extra handling costs compared with from the single supplier. Also reserving the backup paths against the disruption needs additional countermeasures that will add spare loads at the normal state.

Eventually, we propose to view such an intangible attribute as complexity of the network C∈[0, 1] defined by Equation (4.1). It is an inverse index of simplicity, and we prefer to the simple configuration in general.

$$C = (1-w)\left(\frac{m_{RS}}{2|J|} + \frac{m_{CS}}{2|K|}\right)^{\alpha} + w\left(\frac{m_{bk}}{|K|}\right)^{\beta} \tag{4.1}$$

where m_{RS}, m_{CS} and m_{bk} are numbers of multi-served RSs, multi-served customers, and backup paths, respectively. Moreover, w denotes a weighting factor and α and β are elasticity coefficients at the primal and backup states, respectively. Hence each fraction represents normalized value of each number. It makes sense to set these values such that $w=q$, $\alpha<1$ and $\beta>1$ since the abnormal state corresponds to the disruption probability and certain scale merit can reduce the spare loads while urgent tasks will need them increasingly.

Then we depict the relation between the total cost and the complexity in Figure 4.2 where we can observe the tradeoff relation between the cost and the complexity. From this, the optimal network obtained from MSA model seems to be most adequate under present propositions since nearly the minimum total cost can be attained while improving the simplicity considerably. If we could transform this merit into the cost, it is possible to draw a more definite final decision. In our knowledge, however, this is the first attempt to include such an intangible attribute in logistic network design through morphological analysis among the multiple models.

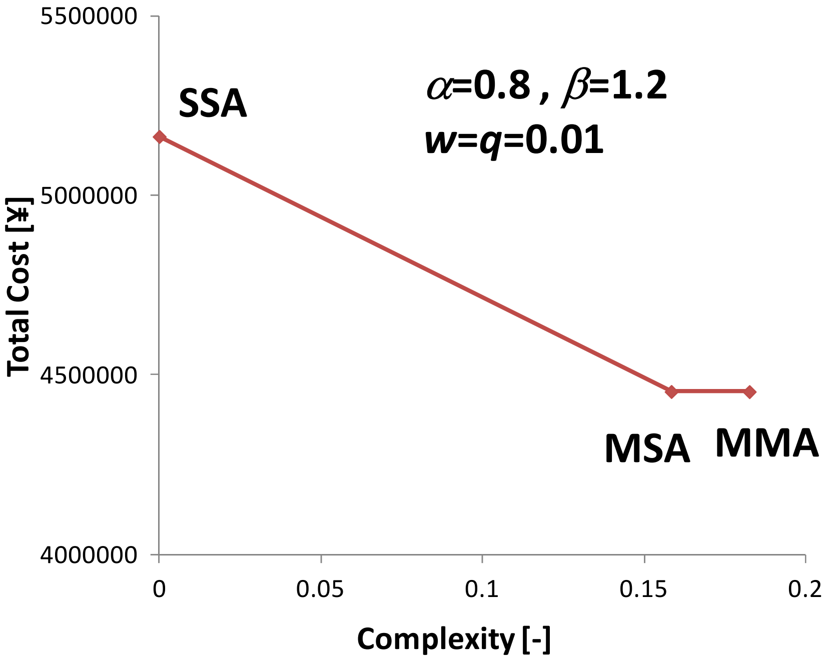


Figure 4.2: Relation between total cost and complexity

4.4 Conclusion

In this chapter, we presented morphological analysis of the three allocation models in multistage logistic network design considering disruption risk. We formulate each model as mixed-integer programming problem and use commercial optimization software to solve the model. Through the numerical experiments, we have shown each model is promising to design the multi-stage logistic networks available for the mitigation planning. Moreover, defining a metric to stand for a certain quality of the structure or complexity, we have shown a procedure to derive a final decision through morphological analysis.

Future studies should be devoted to evaluate the solution ability of the commercial software, and apply the models to some real world applications besides developing a more sophisticated morphological analysis.

Chapter 5

EFFECT OF CONTINUITY RATE

5.1 Introduction

Companies have been facing devastating impacts from unexpected events such as demand uncertainties, natural disasters, and terrorist attacks due to the increasing global supply chain complexity. In this paper, we proposed multi stage logistic network model by considering the effect of continuity rate under disruption risk, which is formulated as Mixed–Integer Programming. We consider varying the fixed charge for opening facilities and the operational costs depend on the continuity rate. The operational level of the company will decrease below the normal condition when disruption occurs. The backup source after the disruption will be recovered not only as soon as possible, but also as much as possible. This is a concept of the business continuity plan in order to reduce the recovery time objective such continuity rate will affect the investment and operational costs. Through numerical experiments, we have shown the proposed idea is promising to design a resilient logistic network available for business continuity management/plan.

Supply chain disruptions have been a challenging issue for companies under the globalization environment. They are unplanned and unanticipated events that disrupt the normal flow of products and materials within a supply chain. The disruption at one members of supply chain can result significant impact on the entire chain. Supply chains are subject to potential external sources of disruption such as natural disaster and terrorist attack.

This study is focused on studying multistage logistic network where the facility can be disrupted partially and still be able to serve below its capacity. Therefore, we consider applying a continuity rate for facilities. This consideration is not taken into account in the previous studies (Rusman and Shimizu 2011, 2012) (Shimizu and Rusman 2012). Consequently, the aim of this study is to compare the properties of the previous model and present model by considering such aspect.

Disruption risk management is one of the emerging topics of supply chain management in the previous decade. Both academics and industrialists try to identify ways to manage the disruption risk and try to minimize the negative impact of supply chain interruptions (Tang 2006). A disruption risk can be defined as the major disruptions caused by natural and man-made disasters such as floods, hurricanes, earthquakes, and terrorist attacks or economic crises such as currency fluctuation or employee strikes (Tang 2006).

There are some previous studies on supply chain considering disruption risk. For instances, Snyder and Daskin (2005) introduced several models based on traditional facility location problems, in which some facilities might fail with a given probability. They assumed that in normal circumstances, customers are assigned to primary facilities and other facilities will serve the customers if the primary facility would fail. Yu *et al*. (2009) studied the impact evaluation on sourcing method in a two stage supply chain in the presence of disruptions risk.

Tomlin (2006) investigated the impact of considering unreliable facilities for the facility location problems. The assumption of Snyder and Daskin (2005) that facility may disrupt with a certain probability is relaxed by Berman et al. (2007), Lim *et al*. (2009) and Cui *et al*. (2010). Lim *et al*. (2009) studied on facility reliability problem (FRP) which is extended from the uncapacitated facility location problem (UFLP). They studied the facility reliability problem (FRP) from the aspect how to design a reliable supply chain network in the presence of random facility disruption. Reliable network design also is considered as strategic supply chain management model that can perform well under normal and abnormal condition (Peng *et al*. 2011).

Considering the risk associated with demand fluctuation, Shimizu *et al*. (2006) applied a flexibility analysis for a three echelon logistic problem. A scenario-based approach is taken to give a solution procedure by recourse model (Shimizu *et al*. 2011).

As the body of the literature about multi-stage logistic network design shows, Mixed-Integer Programming (MIP) models are the common models used in this area. These models range from simple uncapacitated facility location models to complex capacitated multistage or multi- commodity models. The common objective of these models is to determine the least cost system design, which is usually involved tradeoff among fixed opening costs of facilities and operational cost such as transportation costs handling cost and shipping cost. Melo *et al*. (2009) and Klibi *et al*. (2010) present comprehensive reviews on supply chain network design problems to support a variety of future research directions.

Risk can occur in every level of a supply chain, and is recognized as a fundamental link in operating the overall activities and providing value to both firms and customers. Supply chain disruption risk can be defined as the unpredictable or uncertainty of events that can interrupt the overall supply chain or event with a probability that may happen with negative consequences to the supply chain (Tang and Musa 2011). Uncertainty in demand such as demand fluctuation is one of risk source in supply chain. Such method can apply to solve this problem is flexibility analysis, which can be applied in multi echelon logistic network (Shimizu *et al*. 2008).

In the previous literature, most of the models were assumed that a disrupted facility cannot fulfill a part of their assigned demand with available resources. This assumption is not applicable in the real word situations since each facility might fail partially and still able to serve below the expected capacity. Therefore, we consider applying continuity rate on facility, where unreliable facility still can provide demand and also reliable facility decrease its backup ability in an abnormal situation. In this paper, we proposed a multi stage logistic network design model which is formulated as Mixed-Integer Programming (MIP) models by considering the effect of continuity rate under disruption risk.

5.2 Problem Formulation

Among the sources of risk within a supply chain, the risk associated with demand is shown to have a greater impact and higher likelihood of occurrence (Kersten *et al.* 2006). In addition, three-echelon logistics are popular (Shimizu *et al.* 2008) and more flexible compared to two-echelon logistics. In this study, therefore, we focus attention on the demand aspect of the three-echelon logistics.

Having proper backup facilities is an essential element to reduce the RTO in BCP and to create resiliency. We attempted to present a resilient network consisting of major distribution center (DC), sub-DC that takes over the local delivery or relay station (RS) and customer (RE). Generally speaking, since every RS is located nearer to customer site than DC, it is adequate to consider the decision problem at the RS level.

In this research, we concerned with three-echelon logistic problems, which is consisted of distribution centre (DC), relay station (RS) and customer (RE). The location decisions are made in the RS level. In RS level, we proposed two kinds of RS, reliable RS (RRS) and unreliable RS (URS). Then, assuming that DCs are sound safe while RSs potentially affected by the incident, we provided two kinds of RSs, i.e., reliable RSs (RRSs) and unreliable RSs (URSs). URS is no longer available at all for serving customers when it fails or a disruption occurs. This means alternative sources of supply become necessary to provide service to customers. On the other hand, an RRS is stronger and has additional capacity and/or an external alternative sourcing strategy, for example. An RRS can continue fully business even after an incident.

We consider three allocation model, namely multi-multi allocation model (MMA), multi-single allocation model (MSA) and single-single allocation model (SSA). In MMA model, relay station (RS) and customer can receive product from multiple sources. In MSA model, only relay station (RS) can receive product from multiple sources while customer only received product from a single source. In SSA model, both relay station (RS) and customer only received product from a single source.

5.2.1 Without and with model comparison

In this study, we introduced two kinds of model comparison, namely without (*w/o*) model and with (*w*) model. *w/o*-model is multistage logistic network model considering disruption risk, which has been developed in the previous research (Rusman and Shimizu 2011, 2012) without considering continuity rate. *w*-model is the proposed model with considering continuity rate. This model is extended model from the previous approach by modifying the constraints of the model and applied the continuity rate on multistage logistic network design. In these models, we assume that the RS is completely halted when disruption occurs and the backup assignment only from RRS. In this model, RRS is completely reliable to supply the product to customers and URS is completely halted.

We assumed in abnormal situation, *w*-model is more robust and flexible where backup allocation can be supplied from both facilities, RRS and URS, and the maximum backup capacities depend on the continuity rate of facility. In this situation, URS is not completely halted; it still can supply the product to customer as backup assignment with the certain amount depends on the continuity rate of URS (r^U). Total backup capacity of RRS also depends on the continuity rate of RRS (r^R). The continuity rate value (r^U, r^R) is related to the investment cost for opening facility. When the r^U is high, then the investment cost of the facility become expensive but consequence of this cost is backup ability or capacity of URS become higher in abnormal situation. This consideration leads to amend the network to be more robust and flexible in a disruption situation. This assumption is more applicable in the real world applications.

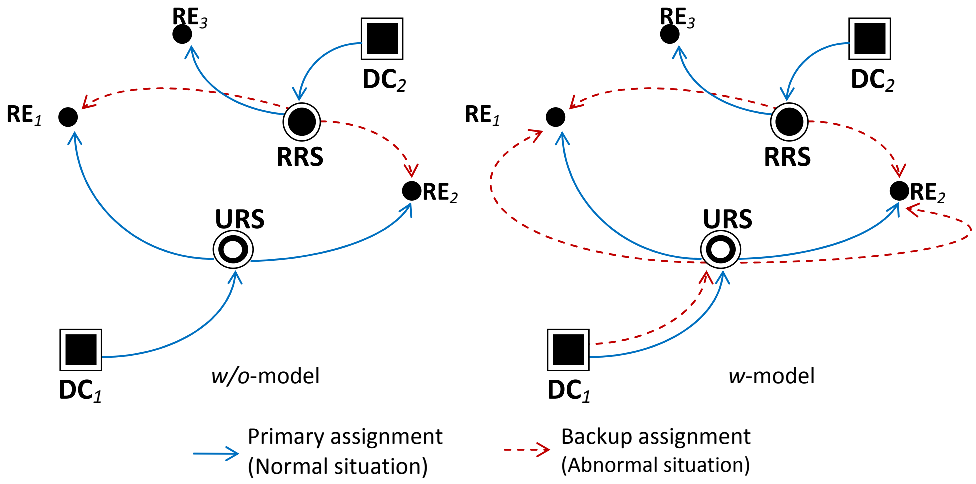
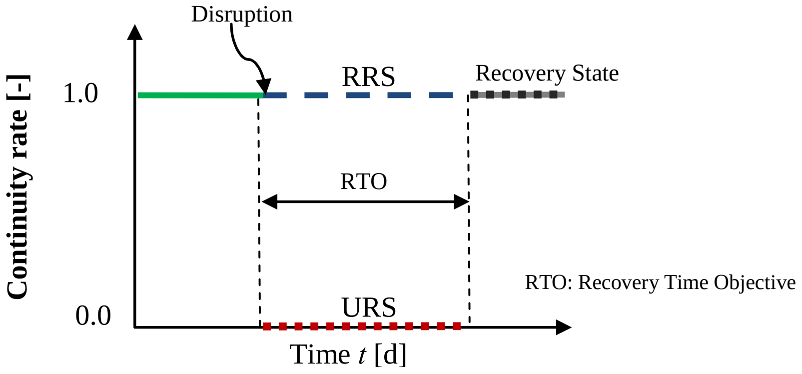


Figure 5.1: The difference configuration for *w/o* and *w* model

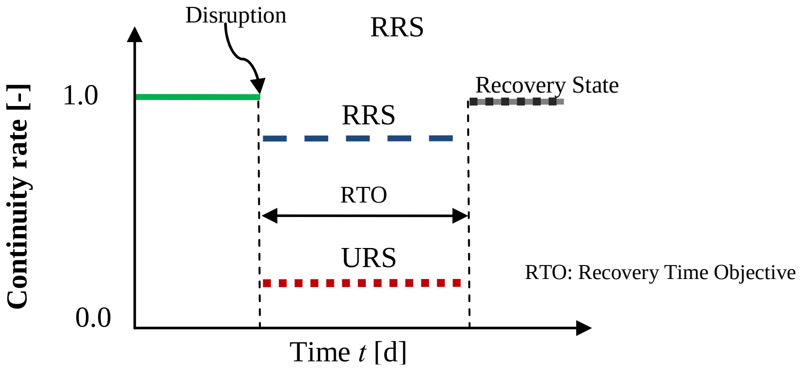
In the traditional model (*w/o*-model), once the network is disrupted, the model intensifies to open more reliable RSs rather than unreliable ones. In the proposed model (*w*-model), network will optimized the backup capacity of URS before considering another backup supply from other RRS. We illustrate the robustness and flexibility of the *w*-model compare to *w/o*-model in Figure 5.1. The main difference between these models is when disruption occurs the URS still can supply product to customer as backup assignment.

This research tries to introduce a parameter called continuity rate. It can ease the solidness for RRS while strength the vulnerability for URS. In Figure 2, we compare the representative schemes of the continuity rate under the previous assumptions (without model or w/o-model, hereinafter) and the present ones (with model or w-model), respectively. After the disruption, the operational level decreases somewhat below the normal condition even for RRS while URS can keep it at a certain level. Thus, the continuity rate is viewed as the operational level during the required time objective (RTO) after the disruption.

When disruption occurs in the facility, the operational level of supply chain activity will decrease below the normal condition. Backup facility will cover the demand of customer in the abnormal condition until the system achieves the recovery state as a normal condition. How fast the system can recover from abnormal condition depend on the continuity rate of facilities and operational supply chain activities. This is the basic concept of the BCP/M, which the purpose is to reduce RTO (Recovery Time Objective) as short as possible. In other words, it must involve a preventive and remediable plan against emergency for management and or decision making to maintain the business continuously.



In case of conventional *w/o*-model



In case of present *w*-model

Figure 5.2: Comparison of continuity rates

5.2.2 Continuity rate

We introduced continuity rate of reliable and unreliable RS (r^R, r^U), continuity rate of shipping (r_p), continuity rate of handling (r_h) and decrease the rate in demand (r_d) on extended model. The value of the continuity rate is denoted in general by r ($0<r\leq 1$) for r = { r^R, r^U, r_p, r_h, r_d }. Generally speaking, building RS with the higher continuity rate needs the higher

investment cost or fixed charge and ultimately an infinite cost for the perfect reliability. This means we can describe the fixed charge as an exponential function of the continuity rates. It is described as r^R and r^U for reliable and unreliable RS, respectively.

The fixed charge for opening RS can be obtained by following the equation.

$$F = \alpha \exp(\beta r) + \gamma, \text{ for } F=\{F^U, F^R\} \text{ and } r=\{r^U, r^R\} \tag{5.1}$$

The fixed cost for opening RS follow the exponential function as shown in Figure 5.3. Fixed cost for URS (F^U) depend on the value of the continuity rate r^U and fixed cost for RRS (F^R) depend on the value of the continuity rate r^R. When we increase the continuity rate (r^U, r^R), then the fixed cost for opening RS is increased follow the exponential function. Particularly for investment RRS which is increased significantly because backup ability increase in an abnormal situation.

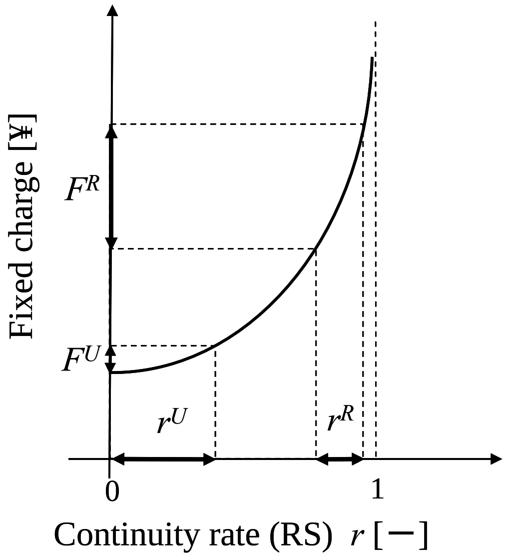


Figure 5.3: Scheme of fixed charge against continuity rate

Regarding the operational cost which is consisted of shipping cost at DC and handling cost at RS assumed follow the linear function as shown in Figure 5.4. We consider the primary shipping cost C^P is equal to the minimum value of the shipping cost C_0. C_1 is the maximum shipping cost.

The backup shipping cost can be obtained by following the equation.

$$C^B = r_p C_0 + (1 - r_P) C_1 \tag{5.2}$$

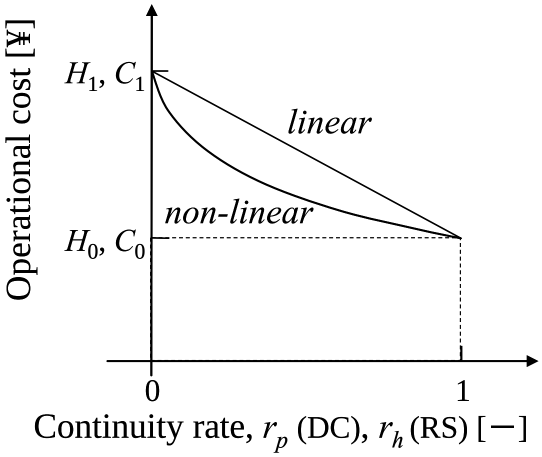


Figure 5.4: Continuity rate graph for shipping and handling cost.

We treat the same condition to obtain the backup handling cost. We consider that the primary handling cost H^P is equal to the minimum of the shipping cost H_0. H_1 is the maximum value of the handling cost. The backup handling cost can be obtained by following the equation.

$$H^B = r_p H_0 + (1 - r_P) H_1 \tag{5.3}$$

To obtained continuity rate of handling (r_h) can be obtained by following the equation.

$$r_h = f_n(r^U, r^R) = (1-w)r^U + wr^R \tag{5.4}$$

In this research we assumed the value of the w (weight) is 0.5. The following notations are used to describe the proposed model.

Additional parameters for continuity model

r^R : Continuity rate of reliable facility
r^U : Continuity rate of unreliable facility
r_p : Continuity rate of production ($0 < r_p \leq 1$)
r_h : Continuity rate of handling ($0 < r_h \leq 1$)
r_d : Decrease rate in demand ($0 < r_d \leq 1$)

5.2.3 Multi-multi allocation model (MMA model)

The model for MMA is described as follows.

Minimize

$$\sum_{j\in J} F_j^U x_j^U + \sum_{j\in J} F_j^R x_j^R$$
$$+(1-q)\left(\sum_{i\in I}\sum_{j\in J}(C_i^P + T1_{ij}^P)a_{ij}^P + \sum_{j\in J}\sum_{k\in K}(H_j^P + T2_{jk}^P)b_{jk}^P\right)$$
$$+(q)\quad\left(\sum_{i\in I}\sum_{j\in J}(C_i^B + T1_{ij}^B)a_{ij}^B + \sum_{j\in J}\sum_{k\in K}(H_j^B + T2_{jk}^B)b_{jk}^B\right) \tag{5.5}$$

The constraints of the objective functions are the same with MMA model in chapter 3, except for equations (3.5), (3.7) and (3.13). We modified these constraints considering continuity rate as shows in equations (5.5) , (5.6) and (5.7), respectively.

$$\sum_{i\in I} a_{ij}^B \le U_j\left(r^R x_j^R + r^U x_j^U\right) \qquad \forall j \in J \tag{5.6}$$

$$\sum_{j\in J} a_{ij}^B \le r_p PU_i, (0 < r_p \le 1) \qquad \forall i \in I \tag{5.7}$$

$$\sum_{j\in J} b_{jk}^B = r_d d_k, (0 < r_d \le 1) \qquad \forall k \in K \tag{5.8}$$

5.2.4 Multi-single allocation model (MSA model)

The model for MSA is described as follows.

Minimize

$$\sum_{j \in J} F_j^U x_j^U + \sum_{j \in J} F_j^R x_j^R$$

$$+(1-q)\left(\sum_{i \in I} \sum_{j \in J} (C_i^P + T1_{ij}^P) a_{ij}^P + \sum_{j \in J} \sum_{k \in K} (H_j^P + T2_{jk}^P) d_k y_{jk}^P \right)$$

$$+(q)\left(\sum_{i \in I} \sum_{j \in J} (C_i^B + T1_{ij}^B) a_{ij}^B + \sum_{j \in J} \sum_{k \in K} (H_j^B + T2_{jk}^B) d_k y_{jk}^B \right) \tag{5.9}$$

The constraints of the objective functions are the same with MSA model in chapter 3, except for equations (3.5), (3.7) and (3.26). We modified these constraints considering continuity rate as shows in equations (5.5), (5.6) and (5.9), respectively.

$$\sum_{i \in I} a_{ij}^B - \sum_{k \in K} r_d d_k y_{jk}^B = 0 \qquad \forall j \in J \tag{5.10}$$

5.2.5 Single-single allocation model (SSA model)

The model for SSA is described as follows.

Minimize

$$\sum_{j\in J} F_j^U x_j^U + \sum_{j\in J} F_j^R x_j^R$$

$$+(1-q)\left(\sum_{i\in I}\sum_{j\in J}(C_i^P + T1_{ij}^P)a_{ij}^P z_{ij}^P + \sum_{j\in J}\sum_{k\in K}(H_j^P + T2_{jk}^P)d_k y_{jk}^P \right)$$

$$+(q)\left(\sum_{i\in I}\sum_{j\in J}(C_i^B + T1_{ij}^B)a_{ij}^B z_{ij}^B + \sum_{j\in J}\sum_{k\in K}(H_j^B + T2_{jk}^B)d_k y_{jk}^B \right) \quad (5.11)$$

The constraints of the objective functions are the same with SSA model in chapter 3, except for equations (3.33), (3.35) and (3.39). We modified these constraints considering continuity rate as shows in equations (5.12) , (5.13) and (5.14), respectively.

$$\sum_{i\in I} a_{ij}^B z_{ij}^B \le U_j (r^R x_j^R + r^U x_j^U) \qquad \forall j \in J \quad (5.12)$$

$$\sum_{j\in J} a_{ij}^B z_{ij}^B \le r_p PU_i, (0 < r_p \le 1) \qquad \forall i \in I \quad (5.13)$$

$$\sum_{i\in I} a_{ij}^B z_{ij}^B - \sum_{k\in K} r_d d_k y_{jk}^B = 0 \qquad \forall j \in J \quad (5.14)$$

5.3 Numerical Experiment and Discussion

In this section, we show the results of numerical experiments. The purpose of these numerical experiments is to compare the total cost between the *w/o*-model and *w*-model. We provided benchmark problems by randomly generating every system parameter within the respective prescribed extents. The probability of disruption q is assumed to be same for $\forall j \in J$, and varied from 0.1 to 0.5. Every node denoting the members of the facilities is also generated randomly. Then, distances between them are calculated based on the Euclidian norm. We obtain the transportation cost by multiplying the unit factor 1.5 and 1.0 with the distance between DC to RS and RS to customer, respectively. Moreover, the same fixed cost that is derived from Equation (5.1) depending on the continuity rate is used both for *w/o* and *w*-models.

We then solved the formulated problems using commercial software known as CPLEX 12.2 on a computer with 2.66GHz core 2 duo processor and 2 GB of RAM.

Table 5.1: Parameter values for small size model

Relay Station (RS)	RS1	RS2	RS3	RS4	RS5
F^U_j	59720	98720	71720	20720	41720
F^R_j	111600	150600	123600	72600	93600
H^P_j	60	82	60	74	86
H^B_j	116	127	126	128	136
U_j	2740	6210	3030	750	1470
$T1^P_{1j}$	1500	1125	1350	1080	1020
$T1^P_{2j}$	615	150	420	120	420

Table 5.2: Parameter values

DC	r_p = 0.8		r_p = 1.0	
	DC1	DC2	DC1	DC2
PU_i	5050	3680	5050	3680
PL_i	500	290	500	290
C_i^P	77	98	77	98
C_i^B	93	108	77	98

5.3.1 Results for small size model

A small numerical example is first presented and analyzed to evaluate the properties of the proposed models towards the resilient system development for multistage logistic network optimization under disruption risk. The scale of the numerical experiment is as follows: the number of distribution centers (DCs) is 2; the number of relay stations (RSs) is 5, and the number of customers (REs) is 50 (Hereinafter such a feature will be denoted as (2-5-50). The parameters of continuity rate for these numerical experiments are given as follows: r^U=0.2, r^R=0.8, r_p=0.8, r_h=0.5. For simplicity, we suppose an identical disruption probability (q) for all RSs and vary q from 0.01 for normal situation and 0.1– 0.5 for abnormal situation. Then, the parameters of continuity rate are changed as shown in Table 5.3.

Table 5.3: Continuity rate of facility (r^U,r^R)

r^R r^U	0.8	0.9
0.1	(Low, Low)	(Low, High)
0.2	(High, Low)	(High, High)

This study tries to present resilient network from DC to customer via RSs which is potentially affected by the disruption. The decision problem is considered at RS level. We evaluate how the change in the critical parameters such as the disruption probability in the RS affects the relative difference (RD) between the expected cost of *w* and *w/o* model. RD is the percentage of difference between expected cost of *w* and *w/o* model, and it obtains by using equation (5.13) and expected cost is defined as EC and relative difference as RD.

$$RD(\%) = \frac{\text{EC of } w/o \text{ model} - \text{EC of } w \text{ model}}{\text{EC of } w \text{ model}} \qquad (5.15)$$

Figure 5.5 shows the result of RD when r_d=0.8. This value tends to decline while fluctuating a bit as *q* grows. Since the *w*-model is considered to be more flexible than the *w/o*-model, the *w*-model outperforms the *w/o*-model for all disruption probability as a generic nature. It is likely the *w*-model opens more URSs than *w/o*-model. By opening more number of URS, *w*-model can reduce the operational cost by providing some products to customers in the abnormal situation. Though URSs in the *w*-model are failed partially in the abnormal situation, they might still be able to serve with a portion of their initial capacity as backups in the abnormal situation depend on the continuity rate (r^U). According to the increase in disruption probability, however, RD will decline as a whole due to the higher rate of RRSs in the opening RSs.

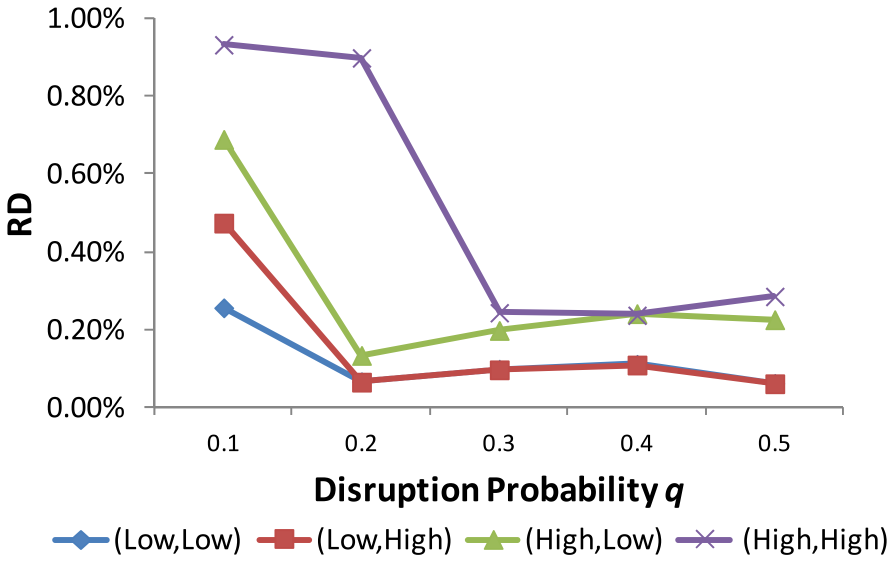
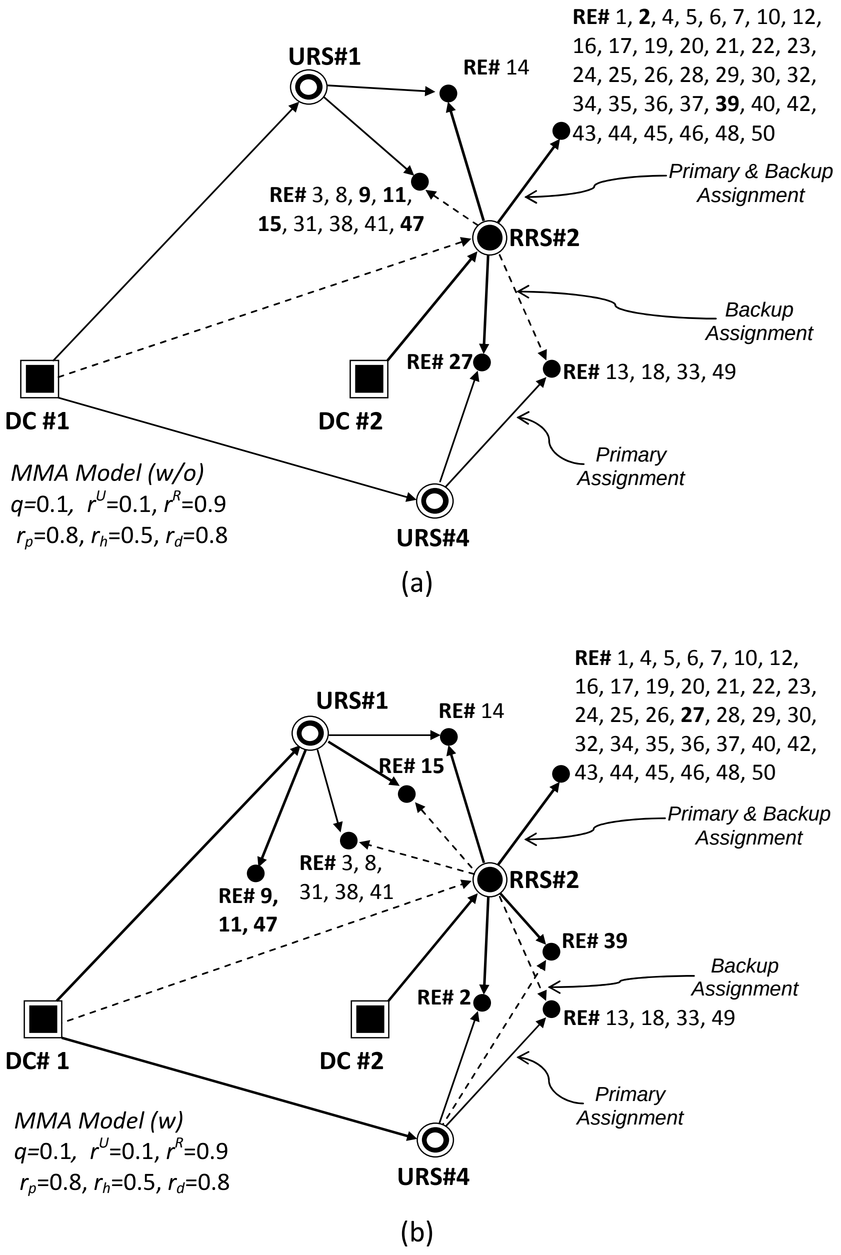


Figure 5.5: Relative difference against disruption

This situation for q=0.1 is depicted in Figure 5.6 for (Low, High) continuity rate setting. Both w/o and w -model open the same types of RS, two URS and one RRS. In the *w*-model, DC#1 will distribute the product not only to RRS#2 but also to URS#1 and URS#4 in an abnormal situation. Moreover, URS#1 and URS#4 also supply some product to customers. On the other hand, *w/o*-model becomes more rigid in the abnormal situation. Thereat, URS#4 is completely stopped the operation and RRSs must supply all customer demands. Such decision is able to reduce the operational cost significantly in *w*-model.



(a)

(b)

Figure 5.6: MMA model comparison between (a) *w/o* and (b) *w*-model for Low- High continuity rate setting

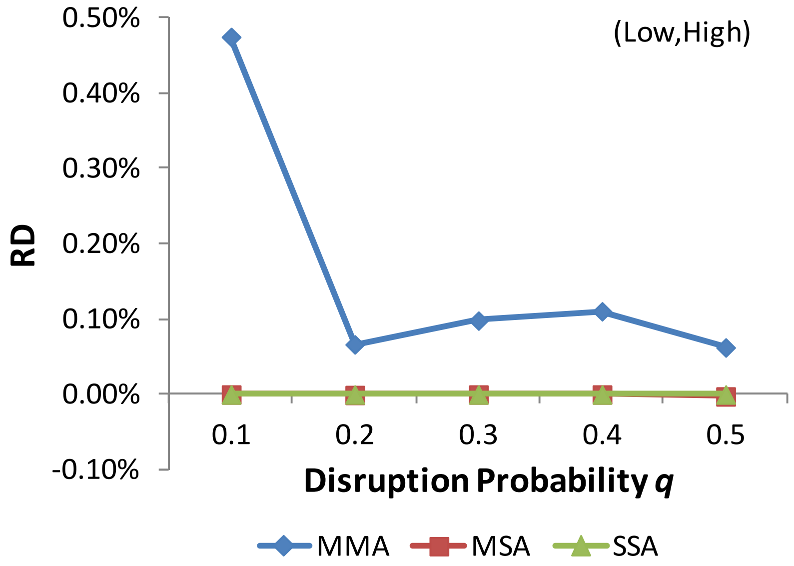


Figure 5.7: Relative difference against disruption probability for each allocation model

This feature is emphasized as shown in Figure 5.7 where we compare the results for every model, i.e., MMA, MSA and SSA. Thereat, RD=0.0 refers to the fact that the opening RSs are almost same between the *w*-model and *w/o*-model for MSA and SSA models. In other word, it was inefficient to overcome the stiffness of configuration just by introducing the parameter like the continuity rate.

The main contribution of cost deduction in *w* model is the ability of URSs to allocate some of backup assignment to customers. This decision will reduce the abnormal cost and will influence the reduction of the expected cost in general. This decision tries to optimize the function of the URS to provide backup assignment in an abnormal situation which is cheaper to open than RRS. We also noted that capacity of RS is also crucial in this model. When the RS open as unreliable with higher capacity RS, the backup ability will also higher in the abnormal situation. We summarized the comparison result among three models for small size problem in Table 5.4.

Table 5.4: Comparison result among three models for (2-5-50) problem

Probability (q)		0.01				0.1				0.3				0.5			
Relay Station		*w*		*w /o*		*w*		*w /o*		*w*		*w /o*		*w*		*w /o*	
		URS	RRS	URS	RRS	URS	RRS	URS	RRS	URS	RRS	URS	RRS	URS	RRS	URS	RRS
No. of facilities (RS#)	MMA	2(#1,4)	1(#2)	2(#1,4)	1(#2)	2(#1,4)	1(#2)	1(#4)	2(#1,2)	1(#4)	2(#1,2)	1(#4)	2(#1,2)	2(#1,5)	2(#2,4)	1(#4)	2(#1,2)
	MSA	2(#1,4)	1(#2)	2(#1,4)	1(#2)	1(#4)	2(#1,2)	1(#4)	2(#1,2)	1(#4)	2(#1,2)	1(#4)	2(#1,2)	0	3(#1,2,4)	1(#4)	2(#1,2)
	SSA	1(#1)	1(#2)	1(#1)	1(#2)	0	2(#1,2)	0	2(#1,2)	0	2(#1,2)	0	2(#1,2)	0	2(#1,2)	0	2(#1,2)
Fixed Cost	MMA	80440	150600	80440	150600	80440	150600	20720	262200	20720	262200	20720	262200	101440	223200	20720	244200
	MSA	80440	150600	80440	150600	20720	262200	20720	262200	20720	262200	20720	262200	0	334800	20720	262200
	SSA	59,720	150,600	59,720	150,600	0	262200	0	262200	0	262200	0	262200	0	262200	0	262200
Normal Cost	MMA	3,342,900		3,342,900		3,342,900		3,342,900		3,342,900		3,342,900		3,338,680		3,372,700	
	MSA	3,343,350		3,343,350		3,343,350		3,343,350		3,343,350		3,343,350		3,343,350		3,343,350	
	SSA	3,418,550		3,418,550		3,418,550		3,418,550		3,418,550		3,418,550		3,418,550		3,418,550	
Abnormal Cost	MMA	4,268,652		4,613,920		4,268,652		4,002,700		3,977,380		4,002,700		3,897,900		4,001,200	
	MSA	5,139,032		5,139,032		4,511,957		4,512,182		4,512,182		4,511,957		4,395,277		4,511,957	
	SSA	5,139,032		5,139,032		4,511,957		4,511,957		4,511,957		4,511,957		4,511,957		4,511,957	
Expected Cost	MMA	3,583,198		3,586,650		3,666,515		3,691,800		3,816,164		3,823,760		3,942,930		3,951,870	
	MSA	3,592,347		3,592,347		3,743,153		3,743,131		3,976,852		3,976,944		4,210,574		4,204,114	
	SSA	3,646,075		3,646,075		3,790,091		3,790,091		4,008,772		4,008,772		4,227,454		4,227,454	
CPU time [s]	MMA	0.05		0.06		0.08		0.06		0.05		0.09		0.08		0.08	
	MSA	0.42		0.22		0.58		0.55		0.53		0.47		1.02		0.78	
	SSA	0.03		0.05		0.08		0.05		0.05		0.05		0.06		0.05	
Gap	MMA	0.00%		0.00%		0.00%		0.00%		0.00%		0.00%		0.52%		0.00%	
	MSA	0.01%		0.01%		0.24%		0.02%		0.02%		0.09%		0.02%		0.25%	
	SSA	0.04%		0.04%		0.03%		0.03%		0.01%		0.01%		0.01%		0.01%	

5.3.2 Results for large size model

The results for the larger problems like (|I|, |J|, |K|) = (4, 15, 150) and (6, 25, 250) are shown in Tables 5.5 – 5.10. The parameters of continuity rate are given as r^U=0.2, r^R=0.9, r_p=0.8 and r_h=0.5, r_d=0.8. These tables show comparison between the *w*-model and the *w/o*-model for three allocation models. Thereat, we summarize the results such as the number of opening facilities, the expected cost, CPU time (in seconds) and GAP as well as the relative difference (RD). Just similar to the small size problem, URS will shift to RRS along with the increase in the disruption probability and the similar profile of RD is observed after all.

We can also know from these tables that the *w*-model outperforms the *w/o*-model both in the (4, 15, 150) and (6, 25, 250) problem sizes for MMA model. This is not the case of MSA and SSA models. Let note that in those models, customers must received the product only from single RS. So when a certain RRS will lose its backup ability, another URS must take for the backup even with higher transportation cost. This situation will lead the increase in the operational cost for the *w*-model in the abnormal situation.

Table 5.5 Result of MMA for 4-15-150

q	*w/o*-model					*w*-model					RD [%]
	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	
0.1	3	2	6,975,890	0.48	0.41	4	1	6,893,214	0.58	0.43	1.20
0.2	3	2	7,273,330	0.59	0.48	4	1	7,137,642	0.53	0.29	1.90
0.3	1	4	7,492,164	0.45	0.38	4	1	7,382,071	0.56	0.00	1.49
0.4	0	4	7,697,519	0.45	0.24	3	2	7,612,965	0.41	0.24	1.11
0.5	0	4	7,893,849	0.31	0.00	3	2	7,831,917	0.42	0.35	0.79

Table 5.6 Result of MSA for 4-15-150

q	*w/o*-model					*w*-model					RD [%]
	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	
0.1	3	2	7,064,103	6.69	0.01	3	2	7,062,914	10.30	0.01	0.02
0.2	2	3	7,448,267	12.64	0.01	3	2	7,447,648	11.64	0.01	0.01
0.3	0	4	7,761,643	13.72	0.01	0	4	7,767,986	17.28	0.01	-0.08
0.4	0	4	8,044,508	7.20	0.01	0	4	8,052,688	12.86	0.01	-0.10
0.5	0	4	8,326,829	6.77	0.01	0	4	8,337,364	4.17	0.01	-0.13

Table 5.7 Result of SSA for 4-15-150

q	*w/o*-model					*w*-model					RD [%]
	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	
0.1	2	2	11,858,824	0.91	0.01	1	3	11,888,565	5.55	0.01	-0.25
0.2	0	5	12,349,457	4.05	0.03	0	5	12,367,278	4.20	0.44	-0.14
0.3	0	5	12,717,037	4.81	0.01	0	5	12,743,695	8.39	0.01	-0.21
0.4	0	5	13,081,549	3.69	0.01	0	5	13,117,093	4.34	0.12	-0.27
0.5	0	5	13,437,014	3.69	0.01	0	5	13,481,735	3.51	0.01	-0.33

Table 5.8 Result of MMA for 6-25-250

q	*w/o*-model					*w*-model					RD [%]
	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	
0.1	3	3	16,392,633	1.56	0.00	3	3	16,323,173	1.56	0.22%	0.43
0.2	2	4	17,037,026	1.50	0.00	3	3	16,911,546	1.31	0.19%	0.74
0.3	1	5	17,605,191	0.98	0.00	3	3	17,499,919	1.58	0.12%	0.60
0.4	1	5	18,170,455	0.80	0.00	4	3	17,262,473	0.50	0.01%	0.54
0.5	1	5	18,735,444	0.72	0.00	4	3	17,828,946	0.55	0.01%	0.51

Table 5.9 Result of MSA for 6-25-250

q	*w/o*-model					*w*-model					RD [%]
	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	
0.1	3	3	16,572,861	37.33	0.01	3	3	16,559,912	44.44	0.00	0.08
0.2	2	4	17,385,035	42.55	0.20	3	3	17,409,941	48.44	0.00	-0.14
0.3	1	5	18,134,846	46.94	0.17	1	5	18,174,377	44.66	0.08	-0.22
0.4	1	5	18,874,895	44.67	0.30	1	5	18,926,209	51.89	0.02	-0.27
0.5	1	5	19,613,861	56.02	0.10	0	6	19,663,671	37.38	0.01	-0.25

Table 5.10 Result of SSA for 6-25-250

q	*w/o*-model					*w*-model					RD [%]
	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	URS	RRS	Expected Cost	CPU time [s]	GAP [%]	
0.1	0	4	24,833,216	4.81	0.01	0	4	24,891,772	4.28	0.01	-0.24
0.2	0	4	25,675,302	4.22	0.07	0	4	25,788,530	3.89	0.00	-0.44
0.3	0	4	26,517,981	2.58	0.01	0	4	26,687,466	3.64	0.01	-0.64
0.4	0	4	27,359,093	2.86	0.01	0	4	27,585,708	1.17	0.01	-0.82
0.5	0	4	28,200,377	3.53	0.01	0	4	28,482,667	3.67	0.01	-0.99

Figure 5.8 shows the comparison of the relative difference (RD) in MMA model with the pair of occurrence of continuity rate already shown in Table 5.5. This figure shows how RD decrease as *q* grows. We also see from this figure that RD has the highest value at *q*=0.2 be-cause the *w*-model opens more number URS than *w/o*-model at this disruption probability. By opening more number of URS that is able to backup within some portion, we can reduce the operational cost in the abnormal situation. Those facts imply allocation of investment highly depends on the disruption probability and relative locations of the logistics members.

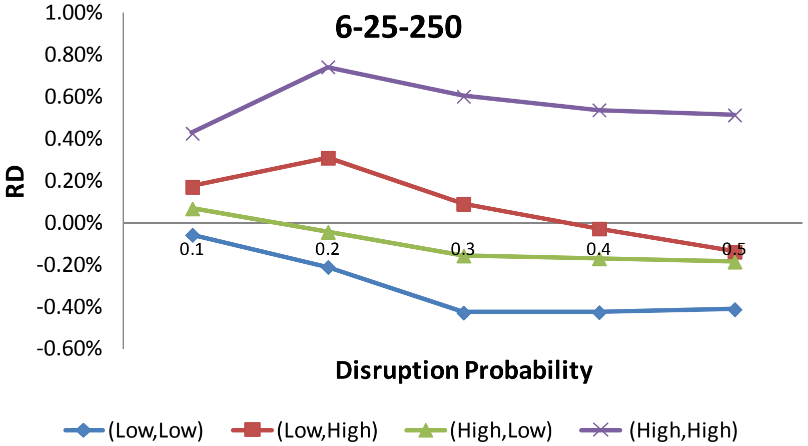


Figure 5.8: Related difference against disruption for large size problem

In Figure 5.9, we show the difference of the total fixed charge for opening facility and the operational which are consisted of the normal cost and abnormal cost for problem size (4-15-150) for both allocation model. For instances for MMA model (Figure 10a) disruption probability *q*=0.2, *w* model open more URS compare to *w/o* model, this decision leads total fixed cost for opening facilities of *w* model becomes higher, but by opening more URS operational cost of the *w* model becomes cheaper compare to *w/o* model.

5.4 Conclusion

In this chapter, we have presented three allocation models in multistage logistic network design considering disruption risk and continuity rate. The continuity rate is a new parameter to formulate the models more practically and make the analysis more comprehensively. Then, we formulated each model as mixed-integer programming problems and used commercial optimization software to solve the models. Through the numerical experiments, we have compared the behavior between the w-model and the w/o-model and shown the flexibility is endowed by introducing the continuity rate.

Future studies will be devoted to evaluating the models for the distributed disruption probability instead of the deterministic one.

Chapter 6

HYBRID APPROACH FOR HUGE MMA LOGISTIC NETWORK

6.1 Introduction

Logistics network design is a critical strategic decision that companies must ensure that required products can be distributed efficiently from plants to distribution centers and distribution centers to relay stations, and the final products to customers. This relates to the determination of the number and location of distribution centers and relay stations and the allocation of customer demand. Network design formulations are used to model a wide variety of problems in several fields such as transportation, logistics and distribution production. In the real-world situation will involve large amount of data, such large data for relay station and customers. With increasing data problems size make it impossible to solve the resulting problem by any currently available software.

In this study concern with the multistage logistic network optimization considering disruption risk and formulated as a mixed-integer programming (MIP) problem. The model formulation refers to combinatorial optimization that can be described as NP-hard with both integer and binary variables. To cope with large data size, complex and complicated real-world situation, in this study, we proposed the Hybrid Tabu search (HybTS) which decompose the original problem into upper level and lower level sub-problems and apply a suitable method for each sub-problem.

Below, presenting the problem formulation and its solution method and the validity of the proposed method is shown through numerical experiments.

6.2 Problem formulation

This study uses the three echelon network for which Shimizu and Rusman (2012) carried out a morphological analysis. The network consists of a distribution center (DC), a relay station (RS), and customers (RE). For RS, we consider two kinds of RS: reliable RS (RRS) and unreliable RS (URS). URS is no longer available to serve customers when the disruption occurs. In contrast, RRS can continue business even after the incident.

Here, for simplicity, we assume that each facility has the same probability of disruption which is denoted by q ($0<q<1$). Primary assignments occur with probability $1-q$ under the normal cost, while backup assignments occur with probability q under the abnormal cost. Moreover, we consider that each RS is able to receive the product from multiple DCs and the customer from multiple RSs depending on the demand of the customer. Finally, we can formulate the model as a probabilistic mixed-integer programming problem as follows.

(p.1) Minimize $\sum_{j\in J} F_j^U x_j^U + \sum_{j\in J} F_j^R x_j^R$

$$+(1-q)\left(\sum_{i\in I}\sum_{j\in J}(C_i^P + T1_{ij}^P)r_{ij}^P + \sum_{j\in J}\sum_{k\in K}(H_j^P + T2_{jk}^P)s_{jk}^P\right)$$

$$+(q)\left(\sum_{i\in I}\sum_{j\in J}(C_i^B + T1_{ij}^B)r_{ij}^B + \sum_{j\in J}\sum_{k\in K}(H_j^B + T2_{jk}^B)s_{jk}^B\right)$$

Subject to

$$x_j^U + x_j^R \leq 1 \qquad \forall j \in J \tag{6.1}$$

$$\sum_{j \in J} x_j^R \geq 1 \tag{6.2}$$

$$\sum_{i \in I} r_{ij}^P \leq U_j (x_j^U + x_j^R) \qquad \forall j \in J \tag{6.3}$$

$$\sum_{i \in I} r_{ij}^B \leq U_j x_j^R \qquad \forall j \in J \tag{6.4}$$

$$\sum_{j \in J} r_{ij}^P \leq PU_i \qquad \forall i \in I \tag{6.5}$$

$$\sum_{j \in J} r_{ij}^B \leq PU_i \qquad \forall i \in I \tag{6.6}$$

$$\sum_{j \in J} r_{ij}^P \geq PL_i \qquad \forall i \in I \tag{6.7}$$

$$\sum_{j \in J} r_{ij}^B \geq PL_i \qquad \forall i \in I \tag{6.8}$$

$$\sum_{i \in I} r_{ij}^P - \sum_{k \in K} s_{jk}^P = 0 \qquad \forall j \in J \tag{6.9}$$

$$\sum_{i \in I} r_{ij}^B - \sum_{k \in K} s_{jk}^B = 0 \qquad \forall j \in J \tag{6.10}$$

$$\sum_{j \in J} s_{jk}^P = d_k \qquad \forall k \in K \tag{6.11}$$

$$\sum_{j \in J} s_{jk}^B = d_k \qquad \forall k \in K \tag{6.12}$$

$$x_j^R \in \{0,1\} \qquad \forall j \in J$$

$$x_j^U \in \{0,1\} \qquad \forall j \in J$$

$$r_{ij}^P \geq 0 \qquad \forall i \in I, \forall j \in J$$

$$r_{ij}^B \geq 0 \qquad \forall i \in I, \forall j \in J$$

$$s_{jk}^P \geq 0 \qquad \forall i \in I, \forall j \in J$$

$$s_{jk}^B \geq 0 \qquad \forall i \in I, \forall j \in J$$

The objective function is the expected cost, which consists of the fixed cost for opening RS, shipping cost at DC, transportation costs between facilities, and handling cost at RS. Equation (6.1) requires that either RRS or URS be open, but not both, and Equation (6.2) requires that at least one RRS must be open. Equations (6.3) and (6.4) are capacity constraints for RS as primary and backup assignments, respectively; Equations (6.5) and (6.6) are the upper bounds of available supply as primary and backup assignments, respectively; Equations (6.7) and (6.8) are the lower bounds of available supply as primary and backup assignments, respectively. Equations (6.9) and (6.10) are the balances of product flow as primary and backup assignments, respectively. Equations (6.11) and (6.12) indicate that the demand of every customer must be satisfied as primary and backup assignments, respectively. Binary conditions are put on x_j^{R} and x_j^{U}, and positive ones on the other variables. Because of some undisrupted reasons, it makes sense to assume a relation for each cost parameter such that $F_j^{\mathrm{R}} > F_j^{\mathrm{U}}$, $T1_{jk}^{\mathrm{B}} > T1_{jk}^{\mathrm{P}}$, $T2_{jk}^{\mathrm{B}} > T2_{jk}^{\mathrm{P}}$, $Ci^{\mathrm{B}} > Ci^{\mathrm{P}}$, and $\mathrm{H}_k^{\mathrm{B}} > \mathrm{H}_k^{\mathrm{P}}$.

Since the formulated problem belongs to an NP-hard class, its solution becomes extremely difficult according to the increase in problem size.

6.3 Hybrid approach for solution

Taking a similar hierarchical logistic network mentioned above, we have proposed a method termed hybrid tabu search (HybTS; Wada and Shimizu 2006) and applied its variants both under the certain and the uncertain cases (Wada *et al.* 2007; Shimizu *et al.* 2008, 2010). It is a two-level method whose upper level problem decides the location of the facilities and the lower derives the routes among them. At the upper level, an evolutionary search is carried out so that the tentative locations are update by sophisticated tabu search. The facility-location pegged problem at the lower level refers to a linier program (LP) that is able to transform into the minimum cost flow problem (MCF).

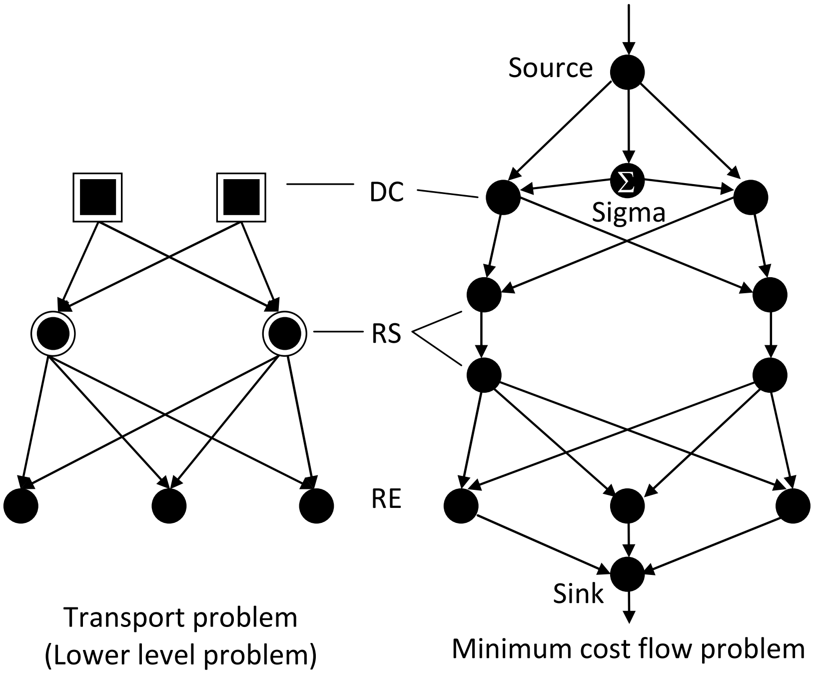


Figure 6.1: Transformed graph from Physical flow

Table 6.1 Label quantities of each edge

From *A* to *B*	**Cost ***	**Upper capacity**
(In) – Source	–	$\sum_{k\in K} d_k$
Source – Sigma	$-M$	$\sum_{i\in I} PL_i$
Source – DC$_i$	C_i	$PU_i - PL_i$
Sigma – DC$_i$	0	PL_i
DC$_i$ – RS$_j^1$	$T1_{ij}$	PU_i
RS$_j^1$ – RS$_j^2$	H_j	U_j
RS$_j^2$ – RE$_k$	$T2_{ij}$	d_k
RE$_k$ – Sink	0	d_k
(Out) – Sink	–	$\sum_{k\in K} d_k$

*Either of primary and backup values, *M*: large value.

To solve MCF effectively, the flow of the physical network will be transformed into the corresponding graph G (*V*, *E*) as shown in both Figure 6.1 and Table 6.1. Node $v\in V$ is a point of flow-in and/or flow-out of product and each edge $e\in E$ has a label denoting the cost and upper capacity of each flow. We can apply a graph algorithm such as CS2 or Relax 4 (Frangioni and Manca 2006) to solve the resulting problem extremely quickly compared with solving the original LP directly. These procedures will be repeated until a certain convergence criterion has been satisfied.

This is idea of HybTS as shown in left hand side of Figure 6.2 can be straightforwardly extended to the present situation by solving the lower level problem for normal and abnormal cases in turn and combining them to compute the expected cost (see the right-hand side of Figure 6.2). Its total procedure is explained briefly and illustrated below.

Step 1: Initial locations of two kinds of RS, i.e., RRS or URS, are decided randomly.

Step 2: Set stage=1 (q=0.0). Moreover, set each parameter to the normal one.

Step 3: Solve the resulting LP using graph algorithm. (This LP is equivalent to the problem that comes from (p.1) by letting q=0.0, and x_j^U, x_j^R, and $\forall j \in J$ are all prescribed at the value decided at Step 1.)

Step 4: If stage=2 (q>0.0), go the next step. Otherwise, set each parameter to the abnormal one. Then, go back to Step 3.

Step 5: Compute the expected cost and update the locations based on the algorithm of the modified tabu search[1]

Step 6: If a certain convergence criterion is satisfied, stop the search. Otherwise, repeat the procedure or go back to Step 2.

---

[1] As the neighborhood operations, three kinds of alteration like a flip-flop type change of randomly selected one node and swapping of randomly selected two nodes are adopted, and the probabilistic search obeyed in terms of the Maxwell-Boltzmann function like SA is introduced besides the tabu list control. See the more detail in the literature (Wada and Shimizu, 2006).

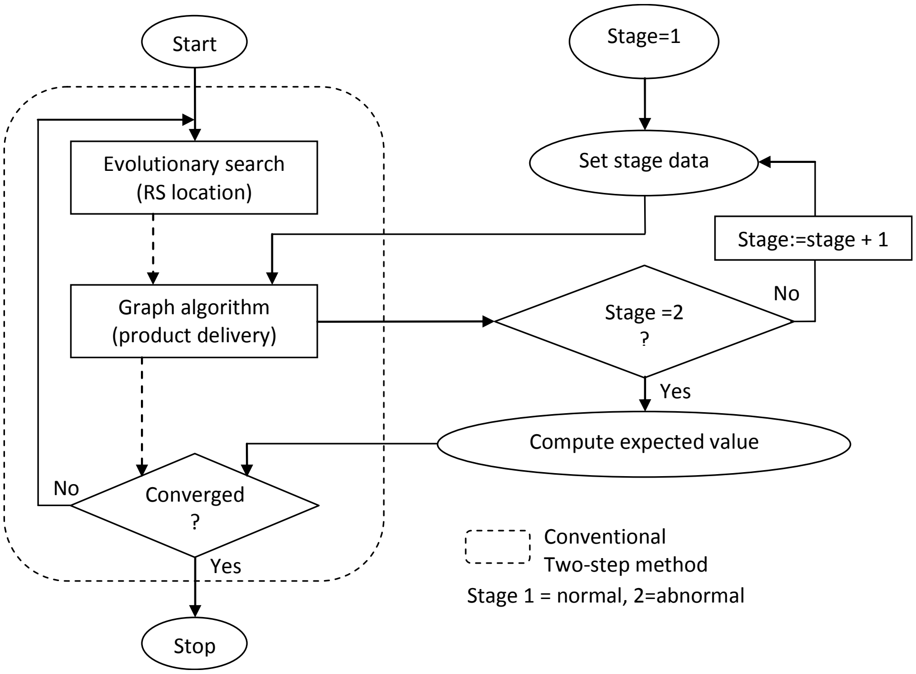


Figure 6.2: Flowchart of the proposed procedure

6.4 Numerical experiments and Discussions

Relying on the above result, we solved several problems with such larger sizes that become unsolvable by the commercial software from our previous experiences revealed in the literature mentioned already. We terminate the search either the iteration attain the prescribed maximum limit or no improvement is realized during a certain consecutive interval. These values are set forth appropriately depending on the problem size.

Figure 6.3 shows profile of each cost against the disruption probability for the problem ((DC-RS-RE) = (10-30-500)). As supposed beforehand, the backup cost is higher than the other costs, and the expected cost gradually decreases and finally coincides with the primal cost when q approaches 0.0. Compared with the change of the expected cost, the other changes seem to almost stay at the same level. However, the structure of the RS members alters greatly and it is difficult to estimate its trend against q as shown in Figure 6.4. Though total number and its breakdown change unexpectedly against the probability, all RS become reliable ones when it becomes highly risky situation, or q=0.5 in this case.

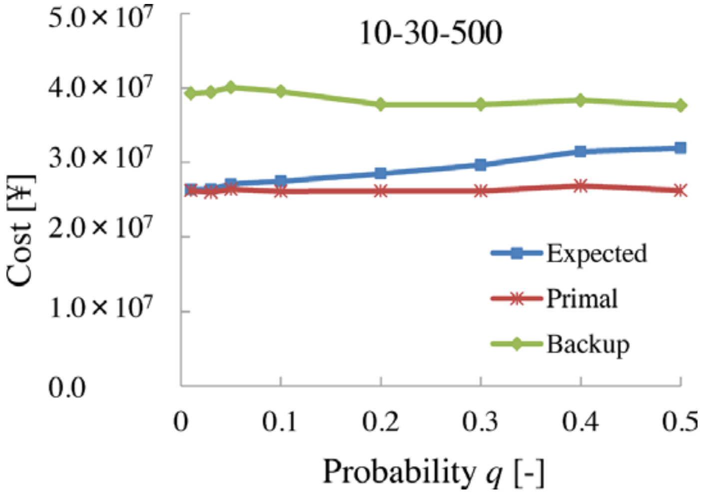


Figure 6.3: Profile of cost against disruption probability

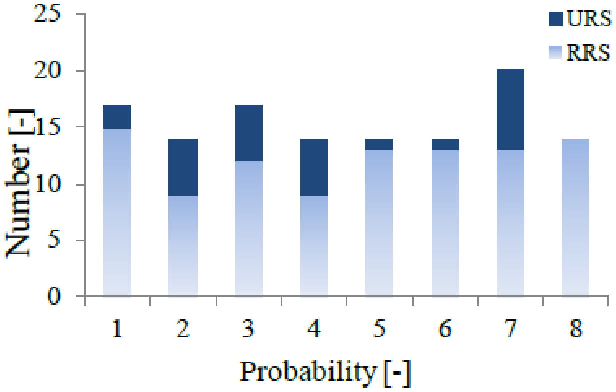


Figure 6.4: Number of RS and its breakdown
(#1~8: q=0.01, 0.03, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5)

Fixing the number of DCs and RSs at 10 and 30, respectively and changing the probability in three cases, i.e., 0.01, 0.1, 0.5, we solved several problems with different numbers of RE up to 5000. This is a huge number not treated anywhere previously.

We summarize the results of three costs in Figure 6.5 and total and breakdown numbers of open RSs in Figure 6.6. The horizontal line of every graph corresponds to the value of probability. Similar to the observation exhibited clearly in Figure 6.5, we need the higher backup cost against the lower disruption probability. Since the chance of incident becomes lower accordingly, its influence will be refrained and can prepare for the disruption with the lower expected cost after all.

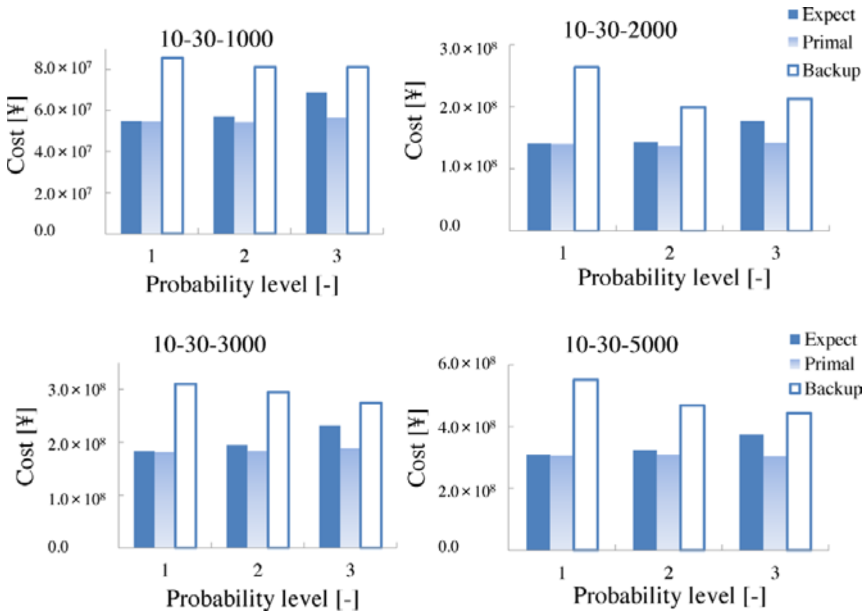


Figure 6.5: Profile of costs against disruption probability (level 1-3: q=0.01, 0.1, 0.5; Expected: solid; Primal: shade; Backup: open)

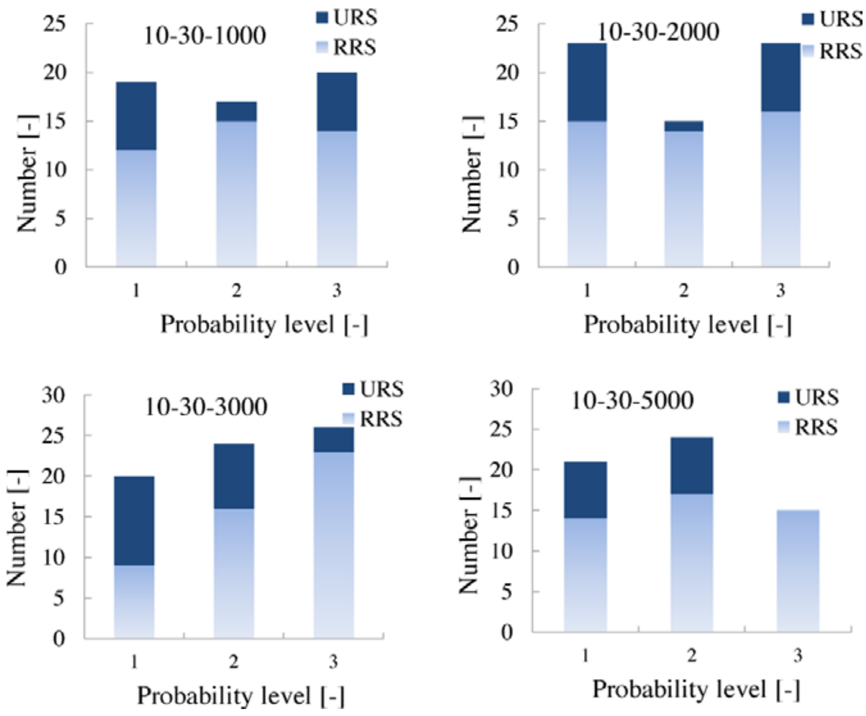


Figure 6.6 Number of RS and its breakdown (level 1-3: *q*=0.01, 0.1, 0,5)

As shown in Figure 6.6, we cannot derive any general feature regarding the number of opening RS against the values of probability. Hence, we can assert the importance of optimization that can lead the appropriate solution depending on the situation.

For each size problem, profiles of convergence are illustrated in Figure 6.7. Due to the generic nature of evolutionary algorithm, we can observe the different patterns thereat. For the problems *RE*=2000 and 5000, after great improvement at the initial stage, a little decrease is observed and seems to gain the convergence finally. The other profiles exhibit different profiles of mild reduction during the initial stage and reach the minimum state.

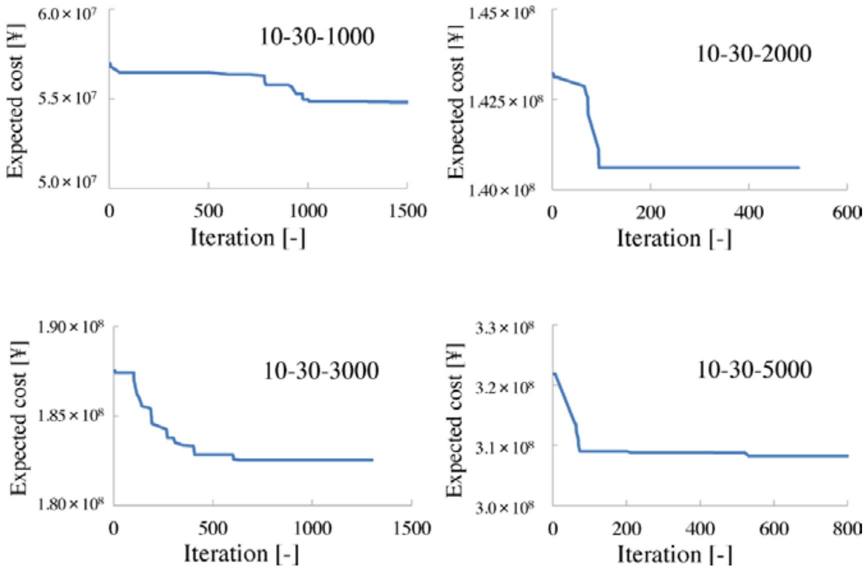


Figure 6.7 Profiles of convergence

Finally, we compared the computational load in Figure 6.8 while fixing the maximum iteration number at the same value (around 1550). This is such a well-known profile that the CPU time increase rapidly along with the problem size. Even for the present biggest size, however, we can complete the search within a half of hour.

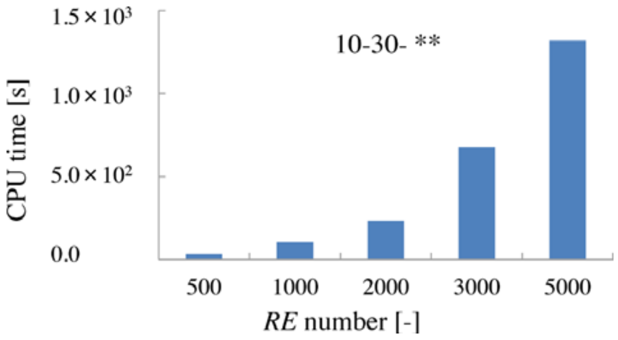


Figure 6.8 Trend of CPU time against problem (q=0.01)

6.5 Conclusion

Associated with the huge supply chain, this study has concerned the multi-stage logistics network designs that are exposed by various risks. The optimization problem is formulated as a probabilistic programming model. To practically find the optimal solution of this problem, a hybrid method is employed that combines a meta-heuristic method and a graph algorithm in a hierarchical manner. Through the numerical experiments, we have shown the proposed approach is promising for designing resilient logistic networks available for real-world mitigation planning.

Future studies should be devoted to enhancing the solution ability by applying the parallel computing technique (Shimizu and Ikeda, 2010), for example, and should consider the more realistic conditions suitable for business continuity planning and management (BCP/BCM).

Chapter 7

CONCLUSIONS AND FUTURE WORKS

7.1 Conclusion

Supply chains are subject to numerous risks of disruptions ranging from natural disasters to terrorist attacks. Although most of these supply chain disruption events occur with very low probability, they often have catastrophic consequences. Such disruptions negatively impact both the financial health as well as the operational performance of the organizations. We identified network designs and operating strategies that make supply chains robust and resilient to random and premeditated disruptions.

In this study, we considered a facility location problem in the presence of random facility disruptions where there are two options of facilities, reliable facility and unreliable facility. In Chapter 3, we presented the comparison result of three allocation models, multi-multi allocation (MMA), multi-single allocation (MSA) and single-single allocation (SSA) model, in multistage logistic network design considering disruption risk. We formulate each model as mixed-integer programming problem and use commercial optimization software to solve the model. Through the numerical experiment, we have shown each model is promising to design the multi stage logistic networks available for the mitigation planning. Additionally, we have conducted a sensitivity analysis in order to understand the effect of changes parameters (*q*, *r*, *r'*) to the total expected cost and the optimal number of open relay station.

In Chapter 4, in this chapter, we presented morphological analysis of the three allocation models in multistage logistic network design considering disruption risk. We formulate each model as mixed-integer programming problem and use commercial optimization software to solve the model. Through the numerical experiments, we have shown each model is promising to design the multi-stage logistic networks available for the mitigation planning. Moreover, defining a metric to stand for a certain quality of the structure or complexity, we have shown a procedure to derive a final decision through morphological analysis.

In Chapter 5, we proposed a new model for supply chain network design by introducing continuity rate on supply chain network design. The proposed model was successful in designing RSs, which are more robust and flexible in an abnormal situation. The optimization problem is formulated as a probabilistic programming model. Through numerical experiments, we have shown the proposed approach is promising for designing resilient logistic networks available for real-world mitigation planning.

In Chapter 6, associated with the huge supply chain, this study has concerned the multi-stage logistics network designs that are exposed by various risks. The optimization problem is formulated as a probabilistic programming model. To practically find the optimal solution of this problem, a hybrid method is employed that combines a meta-heuristic method and a graph algorithm in a hierarchical manner. Through the numerical experiments, we have shown the proposed approach is promising for designing resilient logistic networks available for real-world mitigation planning.

7.2 Future Works

Future studies should be devoted to evaluate the solution ability of the commercial software, and apply the models to some real world applications besides developing a more sophisticated morphological analysis. For future works, one possible extension is to consider sharing product between RS in when disruption occur. Considering this condition in the model will reduce backup transportation cost in an abnormal situation. It is also possible to integrate the model with other decisions such as inventory management and production management.

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PUBLICATIONS LIST

1. Peer-reviewed articles

1.1 Yoshiaki Shimizu and Muhammad Rusman, "A Hybrid Approach for Huge Multi-stage Logistics Network Optimization under Disruption Risk," J. Chem. Eng. Japan, Vol.45, No.8, pp.597-603 (2012)

1.2 Muhammad Rusman and Yoshiaki Shimizu, "Morphological Analysis for Multistage Logistic Network Optimization under Disruption Risk," Journal of Japan Industrial Management Association, Vol.63, No.4E (2013)

2. Conference proceedings

2.1. Yoshiaki Shimizu and Muhammad Rusman, “Morphological Analysis for Multistage Logistic Network Optimization under Disruption Risk,” Proc. International Symposium on Semiconductor Manufacturing Intelligence, Hsinchu, Taiwan (Jan.6-8, 2012)

2.2. Yoshiaki Shimizu and Muhammad Rusman, “Hybrid Approach for Multi-stage Logistics Network Optimization under Disruption Risk,” Proc. 11th International Symposium on Process Systems Engineering, Singapore (July 15-19, 2012)

2.3. Muhammad Rusman and Yoshiaki Shimizu,” Effect of Continuity Rate for Multistage Logistic Network Optimization under Disruption Risk,” Proc. of the Asia Pacific Industrial Engineering & Management Systems Conference 2012, Phuket, Thailand (Dec. 2-5, 2012)