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應用安全存貨及備援廠商管理供應鏈斷鏈風險

Investigation of Solutions for Safety Stock and Backup Supplier Selection for Supply Chain Disruption Risk Management

劉沛玟

Liu, Pei-Wen

指導教授: 許鉅秉 博士

Advisor: Sheu, Jiuh-Biing Ph.D.

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本論文係劉沛玟君（R02741015）在國立臺灣大學商學研究所完成之碩士學位論文，於民國 104 年 06 月 22 日承下列考試委員審查通過及口試及格，特此證明

指導教授：＿＿＿＿＿＿＿＿（簽名）

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誌　謝

研究所的生活一轉眼就到了要結束的時候了，在寫這篇畢業論文的時候，總是會不斷的回想著過去學生生涯的種種一切。雖然過去也是一名管理學院的學生，但對於供應鏈領域可以說是完全的陌生，也從未想到自己可以有機會完成這個學位以及這篇論文。雖然自己也付出了一些努力，但這一路上有太多的人幫助我、提攜我，要感謝的人實在是數都數不盡，因此在這篇論文的一開始，想要先向這些幫助過我的人，獻上我最高的謝意。

首先是我的指導老師－許鉅秉教授，老師是物流管理界的大師，但卻願意花其寶貴的時間指導碩士論文，真的是非常感謝老師。每次若有問題想要請教老師，老師總是不厭其煩的撥空指導我，再加上老師幽默風趣，因此每次找完老師後不僅問題得到了解答，連心情也會好上許多。真的很感謝老師這一年半來的指導與照顧，老師不僅教導我專業領域的知識，更教導我做人處事的道理，使我終身受益。此外，老師更熱心給與我未來繼續就學的建議，真的是位非常替學生著想的老師。在此，特別向許老師獻上我的感謝之意。

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最後是我的家人，家人從小就給我好的環境讀書，讓我衣食不虞匱乏，我能有今天的一點點成就，可以說完全歸功於我的家庭。他們總是無私的照顧我、包容我，讓我勇往直前追求我的夢想。在這裡我要對他們說，謝謝你們、我愛你們。

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摘 要

隨著科技與運輸工具的進步，供應鏈越來越全球化，但也越來越脆弱及易受影響。因此，在當今社會，關於供應鏈風險管理的議題也就越來越重要。當一家公司的供應鏈系統易受其環境影響而變得相當脆弱時，公司的決策者就必須考慮採取減輕策略來因應大環境的衝擊。在本研究中，本文採取了兩種預防性的減輕策略來避免供應鏈系統受到中斷風險嚴重地影響。本文分析了安全存貨及備援廠商兩種減輕策略的特性，接著再將此兩種減輕策略應用在一起以達到最低的運用減輕策略成本為目標。

本文模型主要探討在兩級的供應鏈系統下，當零售商是以採取持續檢視政策及受到隨機需求，並且其補貨來源基本上是來自於一家有可能會遇到中斷危機的主要供應商的情境下所做的討論。在上述的情況下，本研究找出了同時採取此兩種預防性減輕策略並且能夠達到最低目標成本的最適解。通過本研究，可以了解能夠達到最低目標成本的安全存貨與備援廠商的最適分配比例為何。此外，本研究也進行了敏感度分析及情境分析，讓決策者能了解在不同情境下所應採取的行動及分配減輕策略的比例。數值分析的結果證明了本文模型的正確性，並且也提供決策者一個可靠的決策依據，讓其可以在確保最低成本的條件下採取本文模型所建議的減輕策略比例。

關鍵字：供應鏈中斷風險，減輕策略，安全存貨，備援廠商，隨機存貨管理

ABSTRACT

With improvement in technology and transportation, supply chain becomes more international and, unfortunately, more vulnerable. Hence, issues about supply chain risk management are more and more important nowadays. When company's supply chain is very vulnerable to its environment, company's decision maker should consider applying mitigation strategies to survive in this environment. In our research, this study applies two proactive mitigation strategies to prevent our supply chain system from serious disruption risk. This study analyzes the characteristics of safety stock and backup supplier and applies these two mitigation strategies together to achieve the lowest cost of adopting mitigation approaches.

Our model considers stochastic demands with continuous-review system under two-echelon supply chain in which a retailer replenishes its inventory basically from a vulnerable primary supplier who may have a big chance to encounter disruptions. Under this circumstance, this study find out the optimal solution of proactively adopting two mitigation strategies together so as to achieve our objective function, the lowest working inventory cost. This study understands the optimal adopting proportions of backup supplier and additional safety stock that can let us achieve our lowest cost. These studies also do sensitivity analyses and scenario analyses to understand what decision maker should do when under different situations. The results of numerical analysis prove that our model is valid and can really help decision maker to make proper decisions while does not have to worry about drastic changes on total cost.

Keyword: Supply chain disruption risk, Mitigation strategy, Safety stock, Backup supplier, Stochastic inventory management

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Chapter 1 Introduction

1.1 General Background Information

Over the past decades, as technologies and conveyances have been improved, companies are striving to meliorate their financial performance by implementing various supply chain initiatives such as outsourcing and Just-in-Time inventory system. These initiatives are intended to create extra profit through reducing cost, reducing assets, and increasing revenue. However, while companies implement more supply chain initiatives, the whole supply chain system becomes more complex and uncertain. According to an industry study conducted by AMR Research in 2006, over 42% of the companies manage more than 5 different supply chains. (AMR, 2006) The increasing number of supply chains which companies have to manage creates difficulty for companies to manipulate perfectly and also makes the impact of any event become hard or even impossible to predict. These kinds of long and complex supply chains are usually slow to respond to changes, and hence, they are more vulnerable to business disruptions. According to a study conducted by Computer Sciences Corporation in 2004, 60% of the firms reported that their supply chains are vulnerable to disruptions. Therefore, nowadays companies are taking supply chain disruption risk very seriously and trying very hard to avoid it.

Many recent events have shown how disruption impacted the supply chain and global industry. For instance, the huge earthquake in Japan, 2011, was a catastrophe which also followed by a nuclear crisis and caused a significant shortage of electricity on electronics industry. Global suppliers of NAND and DRAM were greatly affected by factories shutdown. Toshiba Corp., a consumer electronics device manufacturer, accounting for 35% of flash memory in the world was also suffered in this earthquake. Figure 1.1 shows that in the second quarter of 2011, Toshiba's revenue and market share of NAND flash memory dropped dramatically and the company lost more than 6% of market share during that period.

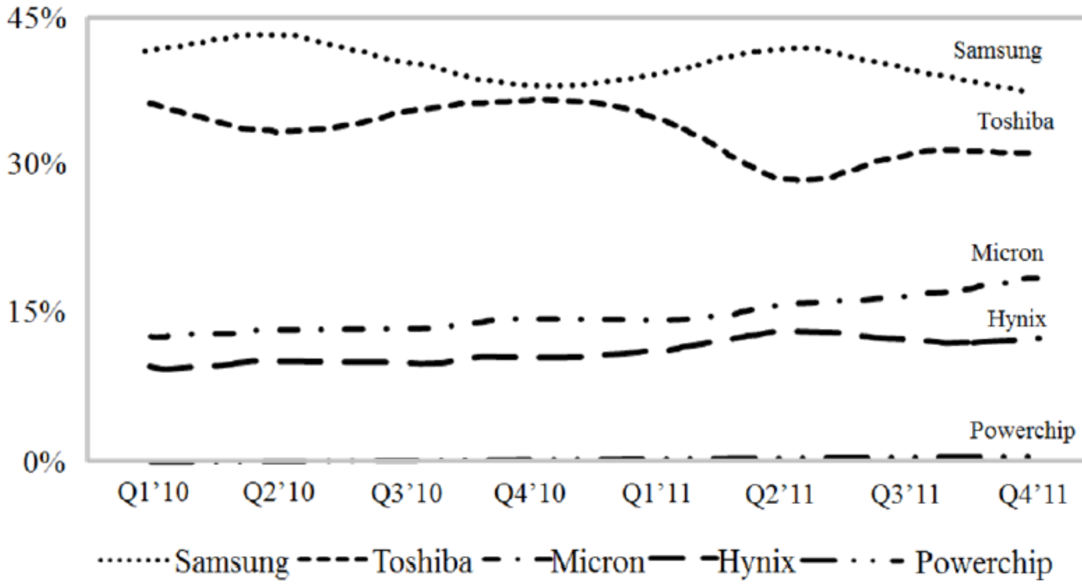


Figure 1.1 Global NAND flash memory revenue market share by quarter.

(Source: Yu-Hsiang Hung, 2013)

Although disruption can be very devastating for companies, if companies can prepare for it in advance, the result of disruption may become not so overwhelming. For example, back in 2000, Telefon AB L.M. Ericsson, a mobile-phone manufacturer, lost nearly 400 million Euros after their supplier's semiconductor plant caught on fire. This supplier was the only provider of Ericsson's microchips, so when this plant shut down after the fire, Ericsson had no other source of microchips, which disrupted production of mobile-phone. On the other hand, a Scandinavian mobile-phone manufacturer Nokia Corp. was also a major customer of that plant, but Nokia began switching its chip orders to other Japanese and American suppliers almost immediately after fire started. Therefore, thanks to its multiple-supplier strategy and responsiveness, Nokia's production suffered little than Ericsson during this crisis. The different outcomes between these two companies show the importance of proactively managing supply chain disruption risk.

Along with the complexity of supply chain evolvement, companies become rigid and hard to response to changes immediately, and hence, become more vulnerable to any possible disruption in the rapidly competitive environment. To protect companies from these risky threats, many researches have been done on studying supply chain risk drivers, sources, and mitigation strategies (Chopra & Sodhi, 2004; Kleindorfer & Saad, 2005; Tang, 2006). These studies focus on specifying risk, distinguishing its sources, and giving some mitigation strategies to reduce the possible impact of disruptions.

Based on these former researches, our research is focusing on finding the balance between those mitigation strategies, hoping to pave a way for dealing with supply chain disruption problems by mathematical models, which can give a lead to decision makers about how to place the best decision about proactive mitigation methods when they manage supply chain. Amanda J. Schmitt (2011) points out that mitigation strategies can be combined together to deal with supply chain disruption problems and give customers' service level protection. But this research stops at giving a proof of the benefits about combining mitigation measures together, and does not mention about the proportion between these strategies. Therefore, our research is going to add this part on combined mitigation methods. While considering two kinds of mitigation strategies, which are safety stock and backup suppliers, and also trying to combine these two methods together to achieve the optimal expected cost under different disruption scenarios. In our mathematical models, this study will show the optimal solutions of the proportions of safety stock and backup suppliers among different scenarios, and hope to shed light on how to distribute disruption mitigation strategies effectively.

1.2 Research Purpose

Based on the above background, our research will integrate topic-related literatures, and try to give a clear outline of supply chain disruption risk and build mathematical models to demonstrate how to adopt disruption mitigation strategies together so as to proactively act on the possible supply chain disruption risk under the lowest cost.

The objectives of this research are:

1. To help decision makers understand how to adopt disruption mitigation strategies effectively and efficiently.
2. To show that the combination of two mitigation strategies, safety stock and backup suppliers, can protect downstream companies effectively when suppliers are all vulnerable to its environment.
3. To demonstrate the benefits of changing proportions of safety stock and backup suppliers under different scenarios.
4. To contribute a literature in building mathematical models for dealing with such supply chain disruption problems.

1.3 Research Scope and Limitation

Although there are lots of mitigation approaches that companies can adopt to their supply chain planning such as production postponement and supply contracts, our research will choose only two mitigation strategies, which are safety stock and backup suppliers, because this study just wants to show that the benefits of combing mitigation strategies together will bigger than only using one mitigation approach alone. Thus, depending on our result of proving the advantage of combination, companies can use as many approaches as they want as long as these are affordable to them and gain benefits from adopting these mitigation strategies together.

This research investigates companies' expected working inventory cost resulting from different disruption levels by adopting safety stock and backup suppliers approaches together under two-echelon supply chain with stochastic demand, whose inventory-control policy is continuous-review policy, and the probability of a disruption occurring at more than one supplier of the same company simultaneously is negligible and that after a disruption the system returns to steady-state prior to another disruption's occurrence.

1.4 Research Framework and Process

In this research, first, this study considers the characteristics of safety stock and backup suppliers which are our mitigation strategies. Next, this study shows how these two approaches can be combined together to create the optimal solution of the lowest cost for companies. Furthermore, this study explores under certain scenarios what distribution of these two strategies should be adopted to provide companies' lowest cost. This study utilizes numerical analysis to show how the proportions of these two strategies can be affected by different situations. Finally, this study draws conclusions and generates some managerial insights in this research, hoping to give decision makers some clues about supply chain planning.

The structure of this research is organized as following: research background, purpose, scope and framework are presented in Chapter 1. In Chapter 2, this study organizes some related literatures to give clear outlines of supply chain disruption risk and its management, safety stock and backup suppliers. This study introduces the model which combines safety stock and backup supplier mitigation strategies together on two-echelon with stochastic demand to achieve the optimal expected cost in Chapter 3. Numerical analysis about the proportions of these two mitigation strategies under different scenarios is illustrated in Chapter 4. The conclusion of our research is presented in Chapter 5 followed with some managerial insights that can be useful in practical world. Figure 1.2 shows the flowchart of this research.

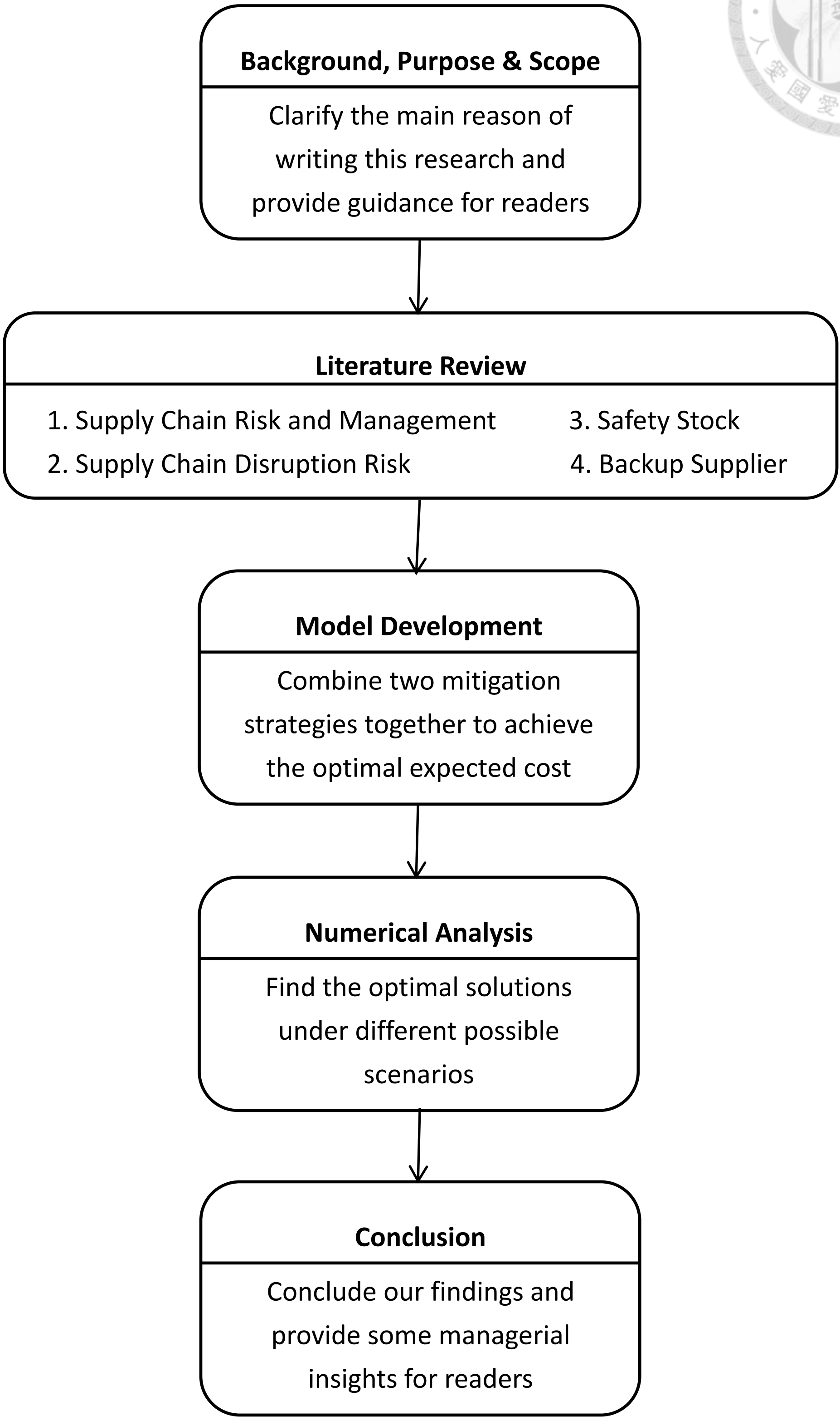


Figure 1.2 Flowchart of this research.

Chapter 2 Literature Review

This research's purpose is to understand the deployment of supply chain disruption mitigation strategies. In this chapter, this study focuses on four dimensions in literature review: supply chain risk and management, supply chain disruption risk, safety stock, and backup supplier. In each sector, this study gives definitions and related information to depict a clear outline of our research content and hope to lead readers to understand this research better.

2.1 Supply Chain Risk and Management

Risk can be broadly defined as a chance of danger, damage, loss, injury or any other undesired consequences and also can be divided into different types according to how its realization impacts on a business and its environment. (Harland, Brenchley & Walker, 2003) Supply chain risk is one of these risk types. According to Heckmann, Comes and Nickel (2014), although the topic of supply chain risk is being considered as increasingly important, there are only a few authors explicitly defining supply chain risk. Among these authors, the first to establish a supply chain risk definition were March and Shapire (1987): they define supply chain risk as the "variation in the distribution of possible supply chain outcomes, their likelihood, and their subjective values". Likewise, Peck (2006) defines supply chain risk as "anything that [disrupts or impedes] the information, material or product flows from original suppliers to the delivery of the final product to the ultimate end-user". Another research effort by Tang (2006) mentions that supply chain risk should refer to (1) events with small probability but may occur abruptly and (2) these events bring substantial negative consequences to the system. In some researches, authors classify supply chain risk into several categories. According to Tang and Tomlin (2008), they categorize supply chain risk to 6 major types which occur regularly: supply risks, process risks, demand risks, intellectual property risks, behavioral risks, and political/social risks. On the other hand, Chopra and Sodhi (2004) classify supply chain risk into 9 categories, including disruptions, delays, systems, forecast, intellectual property, procurement, receivables, inventory and capacity. This study shows the details in Table 2.1.

Table 2.1 Category of risk and drivers of risk

Category of Risk	Drivers of Risk
Disruptions	● Natural disaster ● Labor dispute ● Supplier bankruptcy ● War and terrorism ● Dependency on a single source of supply as well as the capacity and responsiveness of alternative suppliers
Delays	● High capacity utilization at supply source ● Inflexibility of supply source ● Poor quality or yield at supply source ● Excessive handling due to border crossings or to change in transportation modes
Systems	● Information infrastructure breakdown ● System integration or extensive systems networking

	● E-commerce
Forecast	● Inaccurate forecasts due to long lead times, seasonality, product variety, short life cycles, small customer base ● "Bullwhip effect" or information distortion due to sales promotions, incentives, lack of supply-chain visibility and exaggeration of demand in times of product shortage
Intellectual Property	● Vertical integration of supply chain ● Global outsourcing and markets
Procurement	● Exchange rate risk ● Percentage of a key component or raw material procured from a single source ● Industrywide capacity utilization ● Long-term versus short-term contracts
Receivables	● Number of customers ● Financial strength of customers
Inventory	● Rate of product obsolescence ● Inventory holding cost ● Product value ● Demand and supply uncertainty
Capacity	● Cost of capacity ● Capacity flexibility

(Source: Chopra and Sodhi, 2004)

As for supply chain risk management (SCRM), Tang (2006) defines it as "the management of supply chain risk through coordination or collaboration among the supply chain partners so as to ensure profitability and continuity". In addition, Wieland and Wallenburg (2012) define SCRM 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". And they also mention that SCRM can be seen as being "two-sided coin", which can be demonstrated both in proactive and reactive ways to reduce the vulnerability of supply chain. Examples in both ways are shown in Table 2.2.

Table 2.2 Examples for proactive and reactive measures

Strategy	Implementation
Proactive (Robustness)	● Multiple sources of supply ● Inventory ● Make-and-buy ● Product design ● Logistical network design
Reactive (Agility)	● Supplier/buyer communication ● Business continuity planning ● Visibility ● Assortment planning ● Make-to-order/postponement

(Source: Wieland and Wallenburg, 2012)

Furthermore, Chopra and Sodhi (2004) also introduce some general mitigation approaches as following: increasing capacity, acquiring redundant suppliers, increasing responsiveness, increasing inventory, increasing flexibility, pooling or aggregating demand, and increasing capability. These approaches can be selected by companies after they clearly understand their supply chain risk.

In summary, while the definitions in each research of supply chain risk and SCRM are different and few, it is undoubted that these two issues are becoming more and more popular and there are lots of existing researches related to. By clearly understanding the likely risk in companies' supply chain, managers can implement the appropriate strategies to eliminate the possible severe outcome in advance or reduce the level of vulnerability afterward.

2.2 Supply Chain Disruption Risk

Disruption is one of supply chain risk types, according to Chopra and Sodhi (2004). Disruptions can be frequent or infrequent; short- or long-term; and cause problems for the affected organization(s), ranging from minor to serious. Instances of disruption are shown above in Table 2.1. Hou, Zeng and Zhao (2010) define supply chain disruption as the sudden of supply; that is, when unexpected events occur, the main source becomes totally unavailable. And they also describe supply disruption is infrequent risk but has large impact on the whole supply chain, because it could cut off the cash flow and stop the operation of the entire supply chain. In addition, Kleindorfer and Saad (2005) mention that disruption risk can be separated into two categories, which are operational risks (equipment malfunctions, unforeseen discontinuities in supply, human-centered issues from strikes to fraud), and risks arising from natural hazard, terrorism, and political instability. Generally, disruptions often imply the halt of material flow; therefore, although the occurrence of disruption is rare and unpredictable, it is often quite damaging and destructive.

In this point of view, researches about implementing strategies for mitigating disruption risks become more and more. According to Tang (2005), the property that should be included in mitigation strategies is “Resiliency”, meaning the capability to enable a firm to sustain its operation during a major disruption and recover quickly after a major disruption. Besides, Kleindorfer and Saad (2005) give us a clear outline about how to manage disruption risk. They bring out the three tasks as the foundation of disruption risk management, which are: Specifying sources of risk and vulnerabilities, Assessment and Mitigation (SAM). SAM can be briefly explained by steps like understanding the nature of risks, quantifying them, and then, from the result of risk assessment, integrating appropriate management policies to achieve mitigation. Practical strategies to mitigate disruption risks are introduced in Chopra and Sodhi (2004). They consider the best mitigation strategies against disruption risks are (1) adding inventory and (2) having redundant suppliers. These two strategies are proactive approaches to prevent companies from serious damage resulted from supply chain disruptions. There are two reasons to support the strategy of building inventory according to Chopra and Sodhi (2004). First, building inventory does make sense if the disruption can be predicted with reasonable confidence. For example, if companies have learned the impending labor strike beforehand, they can selectively build up inventories so when supply is disrupted as predicted, damage can be minimized by the extra inventory. Second, stockpiling inventory as a hedge against disruption also makes sense for commodity products with low holding costs and no danger of obsolescence. The large petroleum reserve kept by the United States is a perfect example of this strategy. As for products with high holding costs and/or a high rate of obsolescence, according to Chopra and Sodhi (2004), using redundant suppliers is a better strategy. Motorola Inc., for instance, buys many of its handset components from multiple vendors. In addition, companies can lower the cost of redundancy by using multiple suppliers for high-volume products and single sourcing for low-volume products. This approach helps the company lower the risk of disruption while preserving economies of scale at its suppliers. Chopra and Sodhi (2004) also suggest that companies can tailor their response to disruption risk by considering the cost of reserve and product volumes. Table 2.3 shows the tailoring reserves for disruption risk mitigation.

Table 2.3 Tailored strategies for mitigation approach

Mitigation Approach	Tailored Strategies
Increase Inventory	● Decentralize inventory of predictable, lower-value products. ● Centralize inventory of less predictable, higher-value products.
Acquire Redundant Suppliers	● Favor more redundant supply for high-volume products, less redundancy for low-volume products. ● Centralize redundancy for low-volume products in a few flexible suppliers.

(Source: Chopra and Sodhi, 2004)

As reported in Kunreuther (1976), many managers tend to ignore possible events that are very unlikely. Thus, companies usually tend to underestimate disruption risk in the absence of accurate supply chain risk recognition. However, through our introduction about disruption risk, this study can believe that the key point for companies to thrive is to find effective strategies to mitigate the risks of supply chain disruption. Since inventory and redundant suppliers are suggested appropriate approaches to cope with disruption risks, this study is continuing to introduce the literatures about these two topics in next two sections.

2.3 Safety stock

The concept of safety stock is often mentioned in inventory management. The definition in Operations Management (2007) of safety stock is that it is stock which is held in excess of expected demand due to variable demand rate and/or lead time. Another definition of safety stock on BusinessDictionary.com is the inventory held as buffer against mismatch between forecasted and actual consumption or demand, between expected and actual delivery time, and unforeseen emergencies. And it also mentions that safety stock can be called as reserve inventory. According to Stadtler and Kilger (2007), safety stock has to protect against uncertainty which may arise from internal processes like production lead time, from unknown customer demand and from uncertain supplier lead times. They mention that the main drivers for the safety stock level are production and transport disruptions, forecasting errors, and lead time variations. And the benefit of safety stock is that it allows quick customer service and avoids lost sales, emergency shipments, and the loss of good will. Furthermore, safety stock for raw materials enables smoother flow of goods in the production process and avoids disruptions due to stock-outs at the raw material level. Besides the uncertainty mentioned above the main driver of safety stock is the length of the lead time (production or procurement), which is necessary to replenish the stock.

Lots of researches have been done to calculate the optimal safety stock level while considering lead time and demand deviation. One of the most widely accepted methods of calculating safety stock uses the statistical model of standard deviations of a normal distribution of numbers to determine probability. This statistical tool has proven to be very effective in determining optimal safety stock levels in a variety of environments. Two policies are often introduced in operations management textbooks, which are continuous-review policy and periodic-review policy. In Operations Management (2013), the mathematical models for these two policies are as following:

- Safety Stock in Continuous-Review Policy = $Z\sigma_d\sqrt{L}$ (Z means service factor which used as a multiplier with the standard deviation to calculate a specific quantity to meet the specified service level.; σ_d means the standard deviation of demand; L means the fixed lead time).

- Safety Stock in Periodic-Review Policy = $Z\sigma_d\sqrt{P+L}$ (P means predetermined time which is also the reorder period; P + L represents the protection interval, which is the period over which safety stock must protect the user from running out when there are customer demands).

Graves and Willems (2000) also provide a method to optimize safety stock size. They use periodic-review policy to decide how to place safety stocks across the supply chain to provide 100% service for the assumed bounded demand with the least inventory holding cost. In their single-stage model, they represent safety stock as the expected inventory, which depends on the net replenishment time and the demand bound. They also show multi-stage model and algorithm for spanning tree, and then, conclude this research at giving an application in a real world company. In addition, Qi, Shen and Snyder (2009) use continuous-review policy to decide the optimal safety stock level when under supplier disruptions. They find that (1) when the supplier is always available and the downstream retailer is sometimes disrupted, there is no need to hold safety stock at the retailer. (2) If the retailer is never disrupted but the supplier is sometimes unavailable, the retailer should hold safety stock, and the safety stock level should increase as the availability of the supplier decreases. This point of view supports the concept of using safety stock to avoid the disruptions from upstream suppliers and also gives us a reason to adopt safety stock as a mitigation strategy.

In conclusion, there is a large variety of methodological approaches regarding the inventory management processes with disruption risks. Safety stock is one of these approaches. It provides the benefit of protection whether under normal demand fluctuation or emergency disruption situation. Therefore, in our research, we are hoping by adopting safety stock to our model, this study can create the most useful model for decision makers to use when making their supply chain plans.

2.4 Backup supplier

The concept of backup supplier is derived from multiple sourcing strategies. Several researches have proven that multiple sourcing strategies can create benefits when disruption happens, for instance, Burke, Carrillo and Vakharia (2006) and Pochard (2003). According to Gurnani, Mehrotra and Ray (2011), they describe backup supplier like this: Rather than routinely source from multiple suppliers, a firm might instead single source under normal circumstances but rely on an emergency backup supplier in the event of a disruption to its primary supplier. If the emergency backup can respond rapidly when called upon, then an adequate flow of material can be maintained. They also mention that an effective backup sourcing requires proactive planning, and, if necessary, the firm should work to outline better plans to provide backups for certain critical facilities to prevent backups from disruption risk.

Lots of researches about backup supplier investigate the usage of contract. Hou, Zeng and Zhao (2010) use buy-back contract to decide the optimal order quantity to backup supplier and the value of using backup supplier. Saghafian and Van Oyen (2011) use option contract to determine the advance capacity investment/reservation level with a flexible backup supplier and the inventory ordering policy of the underlying products from both primary and backup suppliers. And in this research, they also give us a clue about how important it is to have flexible backup suppliers to use. They investigate the value of implementing flexibility in the backup system showing that contracting with a single flexible backup supplier is better rather than contracting with two inflexible ones. Their study show an average cost reduction of 36%, so flexibility can indeed be highly beneficial; furthermore, it becomes more beneficial as the backup premium increases. Kouvelis and Li (2008) also consider the same point of view. They show that companies should consider the emergency order like this: the later the delivery of the original order, the higher the possibility of using the flexible backup supply. The flexible backup supply is used only when the delivery of the original order is “late” enough. Therefore, from previous researches, this study finds out that not only the contract is important, but also the flexibility, which can be response time and emergency capacity.

For response time, Gurnani, Mehrotra and Ray (2011) show that the backup strategy profit exhibits increasing returns to response time reductions; that is, the incremental benefit to reducing response time is higher the faster the response time. Furthermore, the nature of the disruption (short-frequent or long-rare) plays a crucial role. The profit falls off rapidly in the case of short-frequent disruption; if the emergency supplier cannot respond very quickly then the backup strategy is not effective at mitigating short-frequent disruptions. The profit falls off much more slowly in the case of long-rare disruptions; therefore, there may be a tradeoff between cost, response time and capacity. In the case of long-rare disruptions it may make sense to sacrifice some response time to gain on the other dimensions. Besides, Schmitt (2011) also use response time to be a parameter of backup supplier and use it as a variable in model to decide the expected service level.

As for emergency capacity, Gurnani, Mehrotra and Ray (2011) also show that the profit of a company increases gradually as its emergency capacity of backup supplier increases. The amount of available capacity from backup supplier is a crucial factor to company's profit. Hence, ensuring additional capacity at an external backup source is very important; however, this might require the firm to pay an ongoing fee to reserve a desired level emergency capacity or to contract with multiple suppliers to provide enough backup capacity. In addition, the nature of the disruption also plays a significant role in here. For short-frequent disruptions, the profit is somewhat insensitive to capacity when the response time is long. On the other hand, in the case of rare-long disruptions, the profit increases significantly in capacity even at these longer response times. Therefore, there is a tradeoff between these two flexible factors. If the firm needs short response time, it may face lack of available capacity and vice versa. Thus, simply speaking, when decision makers have to select backup supplier, they can depend on the nature of their possible disruption to deicide the properest backup supplier. For example, response time is a crucial concern for short-frequent disruptions whereas emergency capacity is important for long-rare disruptions.

From these researches, this study notices that response time and emergency capacity play crucial roles in backup supplier strategy; however, in our research, this study will assume our backup supplier is completely flexible, which means it can response quickly to our requirements and always has abundant capacity for us to use, and will not discuss specific details about response time and emergency capacity further in order to simplify the model, but this study suggests that the later research can base on our model and add these two factors to make this model more sophisticated and realistic.

To summarize, supplier diversification and backup sourcing offer alternatives to stockpiling inventory as a means of mitigating disruption risks. By adopting backup supplier strategy, decision makers do not have to stock extra inventory and carry the holding cost. Therefore, this study will use both backup supplier and safety stock in our model and to see which should be adopted more when under different situations.

Chapter 3 Combination of Mitigation Methods

In order to deal with unpredictable supply chain disruption problems, lots of researches have proposed some solutions such as adding inventory and having backup suppliers (Chopra and Sodhi, 2004). In addition, many other literatures discuss this topic with various settings. Our research is based on stochastic continuous-review model (Hillier and Lieberman, 2001), focusing on the benefit providing from proactively applying safety stock and backup supplier mitigation strategies before disruptions happen and investigating the adopting proportion of these two mitigation strategies under different scenarios. In first section, this study will define the problem of this thesis and then introducing our research method and purposes. In second section, this study will introduce some assumptions that help our model more easily to be understood. The last segment will show some notations which will be used in mathematical model and then presenting mathematical model for downstream companies who want to prepare for possible supply chain disruption in advance.

3.1 Problem Definition, Research Method and Purpose

3.1.1 Problem Definition

Our model considers with a disruption risk existing in a two-echelon supply chain retailer (which means manufacturer-retailer). In this two-echelon supply chain, the manufacturer, which is also a primary supplier, is vulnerable to its environment and thus, the order quantities of retailer may be affected by any possible disruption risk of this primary supplier. If a possible disruptive event really occurs, there may only a proportion of order quantities can be delivered on time or none of order quantities can be delivered at all. Hence, in our research, this study wants to find out when a retailer is under this circumstance, what the best policy for a retailer will be to organize its mitigation strategies so as to prepare for disruption risk at lowest cost in advance.

3.1.2 Research Method

Our research uses probability expected value method to form the model. In probability theory, the expected value of a random variable is intuitively the long-run average value of repetitions of the experiment it represents. The expected value can be shown as discrete random variable type and continuous random variable type in mathematical expressions. These two types of expected value computation methods are shown below:

- When x_i is a discrete random variable with probability p_i, computation of the expected value is

$$E = \sum_{I} x_i * p_i$$

x means the resulting value of an event and *p* means the probability of resulting in *x*, which usually ranges from 0 to 1 and can be shown as P ~(0,1).

- When x_i is a continuous random variable and its probability distribution admits a probability density function $f(x)$, computation of the expected value is

$$E = \int x\, f(x)\ dx$$

In our research, this study applies discrete random variable type of expected value computation method to find out what the best solution of proportions of safety stock and backup supplier will be so as to achieve the goal of a retailer, which is to have the lowest expected working inventory cost.

3.1.3 Research Purpose

Our purpose of doing this research is to provide an idea of combining different supply chain disruption mitigation strategies together and show that by using this combination strategy, companies can obtain their optimal results. Therefore, this study uses mathematical modeling method to find out the optimal proportions of safety stock and backup supplier when a retailer is under uncertain time of disruption and uncertain available share of order quantities and, meanwhile, also achieves a goal of the lowest working inventory cost.

3.2 Basic Assumptions

In our model, this study considers a retailer who has two upstream manufacturers, one of these is the primary supplier and the other one is the backup supplier. Two suppliers and one retailer form a two-echelon supply chain system. In addition, our timeline is one year; thus, this study computes yearly working inventory cost.

In this kind of two-echelon supply chain system, this study wants to understand when uncertain time of disruption and uncertain available share of order quantities exist, what is the optimal proportions of safety stock and backup supplier that a retailer will choose. Is more proportion of safety stock better or more proportion of order quantity from backup supplier is better.

In order to simplify the model, this study applies some assumptions as below:

(1) This retailer opens 365 days a year, which also means this retailer works every day and receives demands every day.

(2) There is only one product in this model.

(3) The inventory level is under continuous review policy, also known as (Q, R) policy, so its current value always is known.

(4) The retailer uses traditional EOQ model to decide its (Q, R) policy.

(5) Only the primary supplier has lead time, and the lead time is fixed.

(6) The backup supplier does not have lead time, and its capacity can afford retailer's

regular order quantity, which means retailer can receive its order quantities as long as the order quantities do not exceed its regular order quantity.

(7) The demand for withdrawing units from inventory to sell them is uncertain. However, the probability distribution of demand is known as normal distribution and can be shown as $N \sim (\mu, \sigma^2)$.

(8) If a stockout occurs before the order is received, the excess demand is backlogged, so that the backorders are filled once the order arrives. When a stockout occurs, a fixed shortage cost is incurred for each unit backordered.

(9) A fixed setup cost is incurred each time an order is placed.

(10) A certain holding cost is incurred for each unit in inventory per day.

(11) Each unit of product has fixed procurement cost, and the retailer only has to pay the procurement cost of received quantities.

(12) The procurement cost of backup supplier is always more expensive than the procurement cost of primary supplier.

(13) The probability distribution of occurring disruption in primary supplier is a uniform distribution, and will only occur once in a year and will not occur continuously to next inventory cycle.

(14) The inventory level starts from regular order quantity plus original safety stock in the beginning of a year.

3.3 Model Development

3.3.1 Notations

This study introduces some notations that will be used in our model as below:

Notation	Meaning
K	Fixed setup cost per order for both suppliers
C_p	Procurement cost per unit, including transportation cost, from primary supplier
C_b	Procurement cost per unit, including transportation cost, from backup supplier, and $C_p < C_b$
h	Holding cost per unit per day held in inventory
p	Shortage cost per unit of unsatisfied demand
D	Total yearly demand
d	Random demand per day, assumed to be Normal with mean μ, and variance σ^2, which is shown as $N \sim (\mu, \sigma^2)$
L	Lead time of primary supplier
u	The sum of demand during lead time, as a random variable with mean μL, variance $\sigma^2 L$ and probability density function $\Omega_L(u)$
Q	Regular order quantity for primary supplier, $Q = \sqrt{\frac{2\mu K}{h}}\sqrt{\frac{p+h}{p}}$
θ	Proportion of unavailable order quantities that is going to order from backup supplier, ranging from 0~1. As a decision variable.
$1-\theta$	Proportion of unavailable order quantities that is going to use additional safety stock, ranging from 0~1
ω_i	Random disruption level of primary supplier, ranging from 0~1. Assumed to be Normal with 3 different mean π_i (i= 1,2,3) standing

	for 3 risk preference levels, which are risk seeking, risk neutral and risk avoidance respectively, and $\pi_1 > \pi_2 > \pi_3$, variance s^2
α	Desired service level
Z_α	Normal distribution service factor based on desired service level
N	Number of cycles during a year, $N = \frac{D}{Q}$
j	The cycle that a disruption occurs
R_r	Reorder point at regular situation, $R_r = \mu L + Z_\alpha \sigma \sqrt{L} + (1-\theta)\omega_i Q$
Z_r	Standard score based on R_r, $Z_r = \frac{R_r - \mu L}{\sigma\sqrt{L}} = \frac{\mu L + Z\alpha\sigma\sqrt{L} + (1-\theta)\omega_i Q - \mu L}{\sigma\sqrt{L}} = Z_\alpha + \frac{(1-\theta)\omega_i Q}{\sigma\sqrt{L}}$
R_d	Reorder point after a disruption occurs at primary supplier, $R_d = \mu L + Z_\alpha \sigma \sqrt{L}$

3.3.2 Disruptive two-echelon supply chain system

In our model, there are three characters, which are two suppliers, a retailer and market demand from customers. The retailer faces end market demand and has to place orders to its primary supplier regularly. When a disruption occurs to primary supply chain, primary supplier's delivery will not 100% fulfill the regular order quantity of retailer, which means only $(1-\omega_i)Q$ can be delivered to retailer and the rest of unavailable order quantity $\omega_i Q$ will be ordered from backup supplier or use reserved additional safety stock to fulfill the total order quantity Q.

This study shows the system of our model as below:

◆ Regular situation

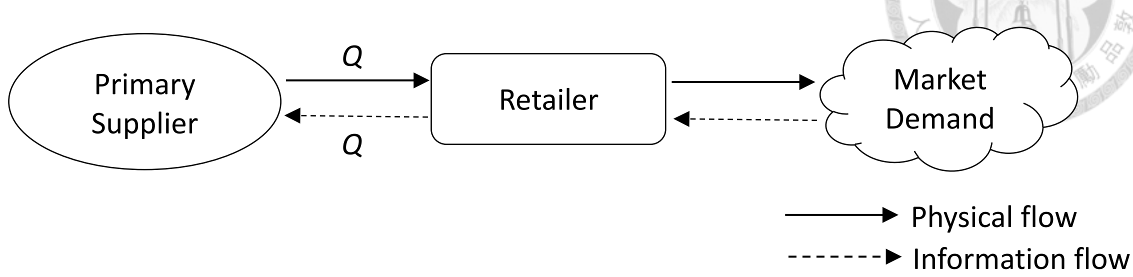


Figure 3.1 Regular situation of two-echelon supply chain network

◆ When a disruption occurs

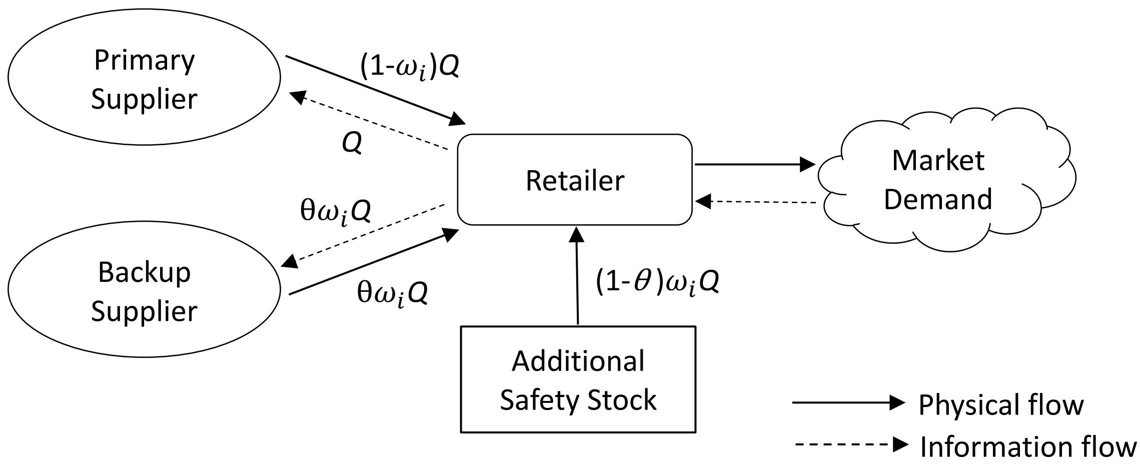


Figure 3.2 Disruptive situation of two-echelon supply chain network

From these two figures above, we can understand that when there is no disruption happens, the flow of entire system is very simple; however, when a disruption occurs, the entire system will become more complex. The retailer has to order the unavailable order quantities from backup supplier to fulfill the rest of regular order quantity. In addition, because our model's intention is to provide a proactive strategy that can help decision makers find out their best policy of additional safety stock and order quantity from backup supplier in advance, this study has to decide the proportion of ordering from backup supplier θ and the proportion of using reserved additional safety stock (1-θ) in advance before a disruption really happens. Therefore, when a disruption actually occurs, decision makers can follow their predetermined policy of proportions of these two mitigation strategies to place an order quantity to their backup supplier with the lowest cost in working inventory of supply chain.

3.3.3 The expected cost of retailer

According to the explanation of former section, we can understand that there will be two situations of cost structure in our model. One is ordering from primary supplier of quantity Q as usual; the other one is ordering a partial unavailable quantity from backup supplier and using reserved additional safety stock to fulfill the rest of regular order quantity Q. Before presenting our model, this study wants to show the inventory policy at the retailer first to see how inventory level changes under different situations. In order to simplify the model, this study sets cycle length $\frac{Q}{d}$ as expected cycle length $\frac{Q}{\mu}$ and will use the expected cycle length $\frac{Q}{\mu}$ in our mathematical model development.

In Figure 3.3, this study can notice that the inventory level with mitigation strategies is higher than the inventory level in normal situation that is because this study uses additional safety stock as a mitigation strategy. In consequence, our inventory level under this situation will be much higher and with extra holding cost of those additional safety stocks, which implies this extra holding cost might be a consideration of our model when deciding the optimal inventory policy.

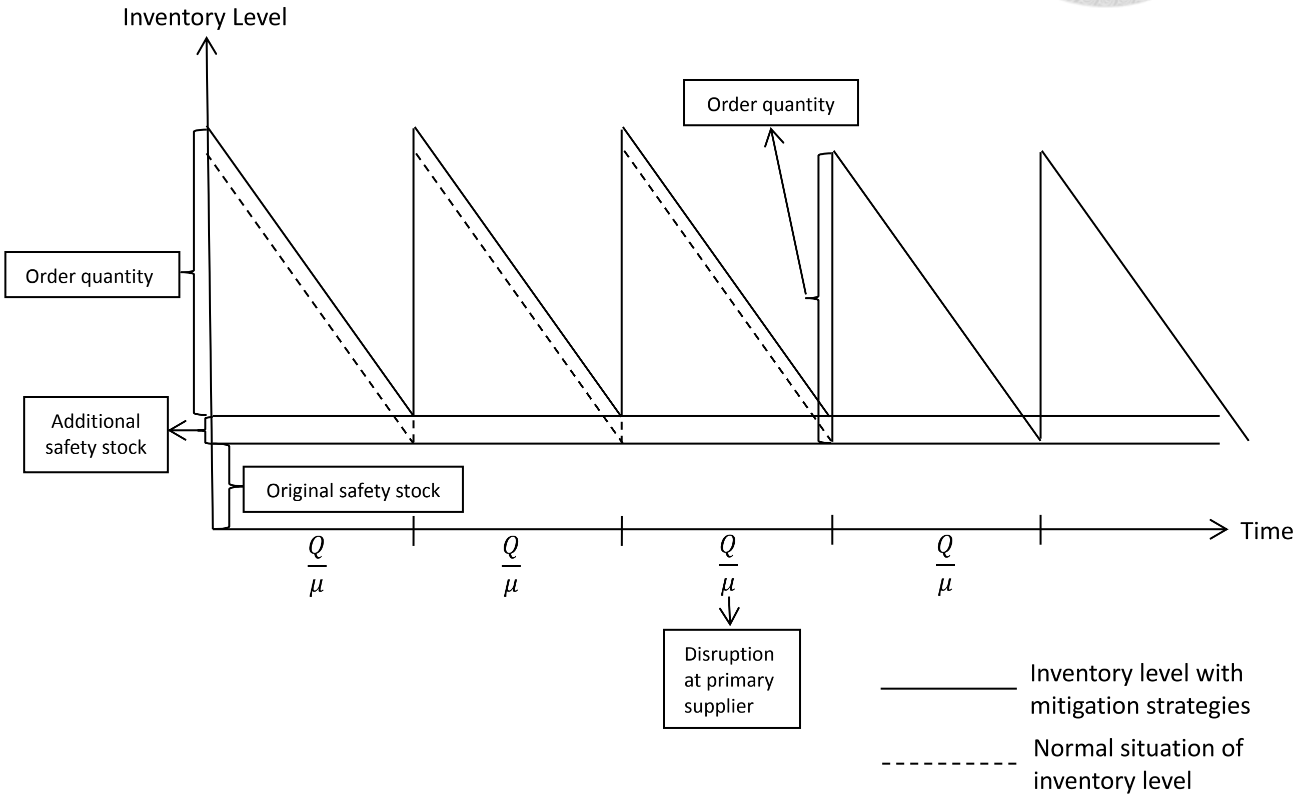


Figure 3.3 Inventory policy at the retailer with cycle length $\frac{Q}{\mu}$

Furthermore, from Figure 3.3, this study can also observe that there is a difference in inventory level after a disruption occurs. Before a disruption, the retailer can order from primary supplier at order quantity Q, and at the same time, will also reserve additional safety stock$(1-\theta)\omega_i Q$ in order to prepare for a sudden disruption at primary supplier. In our model, because this study uses traditional EOQ model to compute order quantity Q and reorder point R, our original safety stock can be computed as $Z_\alpha\,\sigma\sqrt{L}$. Hence, the inventory level before a disruption occurs can be shown as $\frac{Q}{2}+Z_\alpha\sigma\sqrt{L}+(1-\theta)\omega_i Q$.

On the other hand, because when a disruption happens at primary supplier, it will not affect the inventory level that is already held by retailer; it will only influence the inventory level on next cycle, this study can ensure that even though a disruption occurs at a particular cycle, the inventory level of that cycle will still be $\frac{Q}{2} + Z_{\alpha}\sigma\sqrt{L} + (1-\theta)\omega_i Q$. Only the cycles after a disruption will have different inventory level. Because for those cycles after a disruption, according to our assumptions, they will not encounter any disruption again during the same year, they do not have to reserve any additional safety stock which means their inventory level can return to normal situation $\frac{Q}{2} + Z_{\alpha}\sigma\sqrt{L}$.

Based on our previous illustration, this study can introduce our model which will result in the best solution of inventory policy. Our model uses working inventory cost as our objective function. Working inventory cost consists of three types of cost, which are ordering cost, holding cost and shortage cost, respectively. (Qi, Shen & Snyder, 2009)

◆ Ordering cost

Ordering cost includes setup cost and procurement cost. In our model, the ordering cost will be different under various situations. The ordering cost per cycle before a disruption happens, which means retailer can place an order Q to primary supplier, will be $K + C_p Q$. When a disruption occurs at one particular cycle, the ordering cost from primary supplier will be $(Q-\omega_i Q)\, C_p + K$. In addition, because when under a disruption, the retailer will have to order proportion of unavailable order quantity $\omega_i Q$ from backup supplier, the ordering cost from backup supplier will be $\theta\omega_i QC_b$+K. The important thing here is that because this study assumes the inventory level starts from Q+ $Z_\alpha\,\sigma\sqrt{L}$, this study has to order additional safety stock at the beginning of year, whose ordering cost will be $(1-\theta)\omega_i QC_p$+K.

- Holding cost

Since this study has introduced the inventory level under different situations previously, this study can now conclude that the holding cost per cycle before a disruption occurs and at a disruptive cycle will be $\frac{Q^2h}{2\mu}+\frac{\mathrm{Z}\alpha\,\sigma\sqrt{L}Qh}{\mu}+\frac{(1-\theta)\omega_i hQ^2}{\mu}$. On the other hand, the holding cost per cycle after a disruptive cycle will be $\frac{Q^2h}{2\mu}+\frac{\mathrm{Z}\alpha\,\sigma\sqrt{L}Qh}{\mu}$.

- Shortage cost

Shortage cost can also be different when under various situations. Before a disruption happens, the retailer will place an order at reorder point R_r, because the additional safety stock can also be used to compensate demand and be fulfilled again once the order quantity Q arrives. Therefore, the shortage cost per cycle before a disruption occurs will be $p\int_{R_r}^{\infty}(u-R_r)\,\Omega_L(u)du$. When a disruption occurs at a particular cycle, the reorder point will change to R_d, because retailer has to keep additional safety stock on hand to fulfill proportion of unavailable order quantity that will not be satisfied by backup supplier. Under this circumstance, the reserved additional safety stock cannot be used to compensate lead time demand. Thus, the shortage cost at a disruptive cycle will be $p\int_{R_d}^{\infty}(u-R_d)\,\Omega_L(u)du$. After this disruptive cycle, the retailer can return to its normal situation which means its reorder point will be at R_d. Therefore, the shortage cost per cycle after a disruption occurs will also be $p\int_{R_d}^{\infty}(u-R_d)\,\Omega_L(u)du$.

In conclusion, the objective function of working inventory cost will be additional safety stock ordering cost at the beginning of year+ working inventory cost before a disruption occurs+ working inventory cost at a disruptive cycle+ working inventory cost after a disruption occurs.

$$
\begin{aligned}
C(\theta) = {} & (1-\theta)\omega_i Q C_p + K + K(j-1) + C_p Q(j-1) + \frac{Q^2 h}{2\mu}(j-1) \\
& + \frac{Z\alpha\,\sigma\sqrt{L}Qh}{\mu}(j-1) + \frac{(1-\theta)\omega_i h Q^2}{\mu}(j-1) \\
& + p(j-1)\int_{R_r}^{\infty}(u-R_r)\,\Omega_L(u)du + (Q-\omega_i Q)C_p + K + \theta\omega_i Q C_b + K \\
& + \frac{Q^2 h}{2\mu} + \frac{Z\alpha\,\sigma\sqrt{L}Qh}{\mu} + \frac{(1-\theta)\omega_i h Q^2}{\mu} + p\int_{R_d}^{\infty}(u-R_d)\,\Omega_L(u)du \\
& + K(N-j) + C_p Q(N-j) + \frac{Q^2 h}{2\mu}(N-j) + \frac{Z\alpha\,\sigma\sqrt{L}Qh}{\mu}(N-j) \\
& + p(N-j)\int_{R_d}^{\infty}(u-R_d)\,\Omega_L(u)du \qquad (1)
\end{aligned}
$$

In our model, $\Omega_L(u)$ obeys $N\sim(\mu L, \sigma^2 L)$, and according to normal distribution characteristics, we can show that

$$\int_{R_r}^{\infty}(u-R_r)\,\Omega_L(u)du = \sigma\sqrt{L}[\psi(Z_r) - Z_r(1-\Phi(Z_r))]$$

and

$$\int_{R_d}^{\infty}(u-R_d)\,\Omega_L(u)du=\sigma\sqrt{L}[\psi(Z_\alpha)-Z_\alpha(1-\Phi(Z_\alpha))]$$

$\psi(.)$ stands for standard normal probability density function, which can be presented as $\psi(Z)=\frac{1}{\sqrt{2\pi}}e^{-\frac{Z^2}{2}}$, and $\Phi(.)$ stands for standard normal cumulative distribution function, which can be presented as $\Phi(Z)=\int_{-\infty}^{Z}\psi(t)dt$. Therefore, formula (1) can also be written as below

$$\begin{aligned}C(\theta)=&(1-\theta)\omega_i QC_p+K+K(j-1)+C_pQ(j-1)+\frac{Q^2h}{2\mu}(j-1)\\&+\frac{Z\alpha\,\sigma\sqrt{L}Qh}{\mu}(j-1)+\frac{(1-\theta)\omega_i hQ^2}{\mu}(j-1)\\&+p(j-1)\sigma\sqrt{L}[\psi(Z_r)-Z_r(1-\Phi(Z_r))]+(Q-\omega_iQ)C_p+K\\&+\theta\omega_iQC_b+K+\frac{Q^2h}{2\mu}+\frac{\mathrm{Z}\alpha\,\sigma\sqrt{L}Qh}{\mu}+\frac{(1-\theta)\omega_i hQ^2}{\mu}\\&+p\sigma\sqrt{L}[\psi(Z_\alpha)-Z_\alpha(1-\Phi(Z_\alpha))]+K(N-j)+C_pQ(N-j)\\&+\frac{Q^2h}{2\mu}(N-j)+\frac{Z\alpha\,\sigma\sqrt{L}Qh}{\mu}(N-j)\\&+p(N-j)\sigma\sqrt{L}[\psi(Z_\alpha)-Z_\alpha(1-\Phi(Z_\alpha))]\qquad(2)\end{aligned}$$

According to our assumption, because the probability distribution of occurring disruption in primary supplier is a uniform distribution, based on uniform distribution characterization, our expected value of working inventory cost will be the working inventory cost of a disruption at first cycle 1 plus the working inventory cost of a disruption at last cycle N, and then dividing by 2. Thus, this can be shown as below:

$$C(\theta)=\mathrm{E}[C(\theta,Z)]=\frac{C(\theta)\ at\ j=1+C(\theta)\ at\ j=N}{2}$$

this study will use this characterization to compute the expected value of working inventory cost and then using this expected value to find out the optimal policy of θ.

Furthermore, because our model is for proactive mitigation strategy, this study assumes that each decision maker at retailer level will have their own expected disruption level for their primary supplier. Hence, this study will use the expected disruption level π_i to replace random disruption level ω_i to simplify the computation of the expected value of working inventory cost.

When $j = 1$, $C(\theta)$ will be

$$C(\theta) = (1-\theta)\pi_i Q C_p + K + (Q - \pi_i Q)C_p + K + \theta\pi_i Q C_b + K + \frac{Q^2 h}{2\mu} + \frac{\mathrm{Z\alpha}\,\sigma\sqrt{L}Qh}{\mu} + \frac{(1-\theta)\pi_i h Q^2}{\mu} + p\sigma\sqrt{L}[\psi(Z_\alpha) - Z_\alpha(1 - \Phi(Z_\alpha))] + K(N-1) + C_p Q(N-1) + \frac{Q^2 h}{2\mu}(N-1) + \frac{Z\alpha\,\sigma\sqrt{L}Qh}{\mu}(N-1) + p(N-1)\sigma\sqrt{L}[\psi(Z_\alpha) - Z_\alpha(1 - \Phi(Z_\alpha))] \tag{3}$$

and when $j = N$, $C(\theta)$ will be

$$C(\theta) = (1-\theta)\pi_i Q C_p + K + K(N-1) + C_p Q(N-1) + \frac{Q^2 h}{2\mu}(N-1) + \frac{Z\alpha\,\sigma\sqrt{L}Qh}{\mu}(N-1) + \frac{(1-\theta)\pi_i h Q^2}{\mu}(N-1) + p(N-1)\sigma\sqrt{L}[\psi(Z_r) - Z_r(1 - \Phi(Z_r))] + (Q - \pi_i Q)C_p + K + \theta\pi_i Q C_b + K + \frac{Q^2 h}{2\mu} + \frac{\mathrm{Z\alpha}\,\sigma\sqrt{L}Qh}{\mu} + \frac{(1-\theta)\pi_i h Q^2}{\mu} + p\sigma\sqrt{L}[\psi(Z_\alpha) - Z_\alpha(1 - \Phi(Z_\alpha))] \tag{4}$$

Therefore, the expected value $\mathrm{E}[C(\theta, Z)]$ will be

$$\mathrm{E}[C(\theta,Z)] = \frac{Q^2 h}{2\mu} N + \frac{Z\alpha\,\sigma\sqrt{L}Qh}{\mu} N + \frac{(1-\theta)\pi_i h Q^2}{2\mu}(N+1) + KN + 2K + C_p QN + \frac{p(N-1)\sigma\sqrt{L}}{2}[\psi(Z_r) - Z_r(1-\Phi(Z_r))] - \theta\pi_i Q C_p + \theta\pi_i Q C_b + \frac{p(N+1)\sigma\sqrt{L}}{2}[\psi(Z_\alpha) - Z_\alpha(1-\Phi(Z_\alpha))] \quad (5)$$

3.3.4 Differential of the expected working inventory cost

In the section, in order to obtain the optimal solution, this study will use our decision variable θ to do first differential and second differential to the expected value of working inventory cost $\mathrm{E}[C(\theta, Z)]$ to find the lowest working inventory cost.

Among formula (5), there is $\psi(Z_r) - Z_r[1-\Phi(Z_r)]$, and its first differential at θ will be, according to the Chain Rule

$$\frac{\partial\, \psi(Z_r) - Z_r[1-\Phi(Z_r)]}{\partial\, \theta} = \frac{\partial\, \psi(Z_r) - Z_r[1-\Phi(Z_r)]}{\partial\, Z_r}\frac{\partial\, Z_r}{\partial\, \theta} = [\Phi(Z_r) - 1]\frac{-\pi_i Q}{\sigma\sqrt{L}}$$

Therefore, the first differential of $\mathrm{E}[C(\theta, Z)]$ at θ will be

$$\frac{\partial\, \mathrm{E}[C(\theta,Z)]}{\partial\, \theta} = -\frac{\pi_i h Q^2 N}{2\mu} - \frac{\pi_i h Q^2}{2\mu} + \frac{p\pi_i Q(1-N)}{2}\Phi(Z_r) - \frac{p\pi_i Q(1-N)}{2} - \pi_i Q C_p + \pi_i Q C_b \quad (6)$$

Let the first differential $\frac{\partial\, \mathrm{E}[C(\theta,Z)]}{\partial\, \theta} = 0$ to obtain the optimal solution of $\Phi(Z_r)$

$$\Phi(Z_r) = \frac{2\left(C_b - C_p - \frac{Qh(N+1)}{2\mu} + \frac{p(N-1)}{2}\right)}{p(N-1)} \quad (7)$$

thus,

$$Z_r = \Phi^{-1}\left[\frac{2\left(C_b - C_p - \frac{Qh(N+1)}{2\mu} + \frac{p(N-1)}{2}\right)}{p(N-1)}\right] \quad (8)$$

and in order to simplify, let $\Phi^{-1}\left[\frac{2\left(C_b - C_p - \frac{Qh(N+1)}{2\mu} + \frac{p(N-1)}{2}\right)}{p(N-1)}\right] = \beta$; furthermore, because $Z_r = Z_\alpha + \frac{(1-\theta)\omega_i Q}{\sigma\sqrt{L}}$, we can understand that

$$Z_r = Z_\alpha + \frac{(1-\theta)\pi_i Q}{\sigma\sqrt{L}} = \Phi^{-1}\left[\frac{2\left(C_b - C_p - \frac{Qh(N+1)}{2\mu} + \frac{p(N-1)}{2}\right)}{p(N-1)}\right] = \beta$$

Hence, this study can obtain θ as

$$\theta = \frac{Z_\alpha \sigma\sqrt{L}}{\pi_i Q} - \frac{\beta\sigma\sqrt{L}}{\pi_i Q} + 1 \quad (9)$$

And then doing the second differential of $\mathrm{E}[C(\theta, Z)]$ at θ

$$\frac{\partial^2\,\mathrm{E}[C(\theta,Z)]}{\partial\,\theta^2} = \frac{\partial}{\partial\,\theta}\left[\frac{\partial\,\mathrm{E}[C(\theta,Z)]}{\partial\,\theta}\right]$$

$$= \frac{\partial\,\left[-\frac{\pi_i h Q^2 N}{2\mu} - \frac{\pi_i h Q^2}{2\mu} + \frac{p\pi_i Q(1-N)}{2}\Phi(Z_r) - \frac{p\pi_i Q(1-N)}{2} - \pi_i Q C_p + \pi_i Q C_b\right]}{\partial\,\theta}$$

According to the Chain Rule, we know that

$$\frac{\partial\,\Phi(Z_r)}{\partial\,\theta} = \frac{\partial\,\Phi(Z_r)}{\partial\,Z_r}\frac{\partial\,Z_r}{\partial\,\theta} = \psi(Z_r)\frac{-\pi_i Q}{\sigma\sqrt{L}}$$

Therefore, the second differential of $\mathrm{E}[C(\theta,Z)]$ at θ will be

$$\frac{\partial^2 \mathrm{E}[C(\theta,Z)]}{\partial \theta^2} = \frac{p{\pi_i}^2 Q^2 (N-1)}{2\sigma\sqrt{L}} \psi(Z_r) > 0 \tag{10}$$

Because $N > 1$ and probability density function $\psi(Z_r)$ is always positive, the second differential of $\mathrm{E}[C(\theta,Z)]$ at θ will always be positive, too. This shows that the function of working inventory cost $C(\theta) = \mathrm{E}[C(\theta,Z)]$ is a convex function. Hence, the solution from the first differential is the optimal solution that can let working inventory cost be minimum.

There is something very important that this study should be noticed in here. Although this study has already successfully obtain the optimal solution of decision variable θ, there is a constraint for us to gain this result, which is $\Phi(Z_r)$ should smaller than or equal to 1. Thus, formula (7) should have a constraint as

$$\Phi(Z_r) = \frac{2\left(C_b - C_p - \frac{Qh(N+1)}{2\mu} + \frac{p(N-1)}{2}\right)}{p(N-1)} \leq 1$$

and then this study can obtain the result that

$$2(C_b - C_p) \leq \frac{Qh(N+1)}{\mu} \tag{11}$$

This result shows that there is a relationship between the price difference in two suppliers $C_b - C_p$ and the holding cost per unit h. This kind of relationship means that the retailer who will want to apply our model as its mitigation strategy is definitely has quite an amount on its holding cost per unit. This relatively huge holding cost will cause retailer to consider of applying backup supplier to become its mitigation strategy as well. Because if the holding cost is very small, retailer can have the lowest inventory cost by just reserving more additional safety stock and do not need to use backup supplier as its second mitigation strategy. This conclusion will affect our numerical analysis when this study tries to provide some parameters for C_b, C_p and h. Therefore, this study should pay attention to this relationship in Chapter 4.

In conclusion, this study can use formula (9) to understand when the retailer is under different expected disruption levels, which may be influenced by decision maker's risk preference level, what will be the optimal policy of proportions of backup supplier and additional safety stock. In next chapter, this study will do numerical analysis that will apply actual data to make this model more comprehensible.

Chapter 4 Numerical Analysis

The intention of our mathematical model is to provide guidance for downstream decision maker, which in our case is the retailer, to find out the optimal policy of their supply chain disruption mitigation strategies with the lowest cost.

In order to analyze our model, this study uses the most broadly used software – EXCEL to compute all data analysis. Although EXCEL is the simplest software when running a numerical analysis, this is exactly the reason why this study uses this software to run our numerical analysis. Because EXCEL is one of the most commonly used software and the simplest software in industry, this study can ensure that our model can be used by decision makers smoothly and without any difficulty.

To solve our mathematical model, this study gives the model some real parameters. Although these parameters are dummy, this study should not be rigid in these numbers because these parameters are just intended to provide reference for decision makers when they are going to find the optimal solution.

This study shows some parameters on the character of retailer and these parameters are shown below in Table 4.1. Any parameter that involves with cost is in US dollar.

Table 4.1 The parameter settings for retailer

Parameter	**Value**	**Parameter**	**Value**
K	$20/order	μ	30 unit/day

C_p	$6/unit	σ^2	25 unit/day
C_b	$8/unit	L	5 day
h	$0.03unit/day	α	0.95
p	$10/unit	Z_α	1.645

And then this study can use Table 4.1 to compute other parameters that this study needs, we present these parameters with formulas in Table 4.2.

Table 4.2 Other parameter settings for retailer

Parameter	**Formula and Value**
D	$= \mu * 365 = 30 * 365 =$10950 unit/year
μL	$= \mu * L = 30 * 5 =$150 unit
$\sigma\sqrt{L}$	$= \sigma * \sqrt{L} = 5 * \sqrt{5} =$11.18 unit
Q	$= \sqrt{\frac{2\mu K}{h}}\sqrt{\frac{p+h}{p}} = \sqrt{\frac{2*30*20}{0.03}}\sqrt{\frac{10+0.03}{10}} =$200.3 unit
N	$= \frac{D}{Q} = \frac{10950}{200.3} =$54.67 cycle/year

Although this study has introduced all these parameters above, this study should notice that, as this study mentioned previously, there is a relationship between price difference of two suppliers $C_b - C_p$ and holding cost per unit h. Therefore, when this study applies numbers on these three costs, this study should follow formula (11), which is an inequality between $C_b - C_p$ and h. This study shows the relationship between these two parameters in Figure 4.1.

Figure 4.1 Relationship of price difference of two suppliers and holding cost

From Figure 4.1, this study can understand that as the holding cost h increases, the range of price difference will increase as well. This relationship can be roughly presented as a linear function $C_b - C_p = 183.02h + 0.0845$. Hence, if retailer's holding cost is relatively more expensive, its acceptable range for price difference between two suppliers will also be relatively wide, and after knowing this result, retailer can depend on it to find its reasonable procurement cost of backup supplier.

In real world, the retailer is definitely aware of its holding cost per unit per unit time and its procurement cost per unit from primary supplier, so retailer can use formula (11) to find out its reasonable price range of the potential backup supplier. For instance, in our case, because this study knows that the holding cost h is $0.03 unit/day, the reasonable price difference range between two suppliers will be $5.57. Furthermore, because this study sets procurement cost of primary supplier to be \$6/unit, we can know that our reasonable procurement cost range of potential backup supplier must be smaller than \$11.57. Furthermore, logically speaking, the price of backup supplier should not be cheaper than primary supplier; otherwise retailer will change backup supplier as its primary supplier. Hence, the price range of the potential backup supplier should be from \$6 to \$11.57 per unit. And this study chooses \$8 to be the parameter of procurement cost of backup supplier. This study will discuss this relationship further in sensitivity analysis.

4.1 Numerical Example

In this section, this study will use parameters above to simply run our model and show the results of our decision variable θ.

As this study mentioned in Chapter 3, because each retailer is probably aware of its primary supplier's possible disruption level, this study will apply three different expected disruption levels respectively to represent what three different risk preference level of decision makers are going to encounter. This study shows the expected disruption level for each risk preference level respectively in Table 4.3.

Table 4.3 The expected disruption level for each risk preference level

Risk preference level	**Expected disruption level**
Risk seeking	80%
Risk neutral	50%
Risk avoidance	10%

Although all parameters above are the same to these three different risk preference levels, this study assumes that for risk seeking retailer, its primary supplier is much more unreliable than risk avoidance retailer. Because this kind of retailer finds its primary supplier without any extra effort and without any serious check, the risk seeking retailer will be more vulnerable at primary supplier than risk avoidance retailer.

This study puts all parameters above in our mathematical model, and we can get our optimal solution of decision variable and expected working inventory cost under different expected disruption level. The result is in Table 4.4.

Table 4.4 The optimal solution under different expected disruption level

Expected disruption level	**Proportion of backup supplier**	**Proportion of additional safety stock**	**Expected cost (US$)**
80%	0.960	0.04	$68,553.7
50%	0.936	0.064	$68,433.5
10%	0.681	0.319	$68,273.3

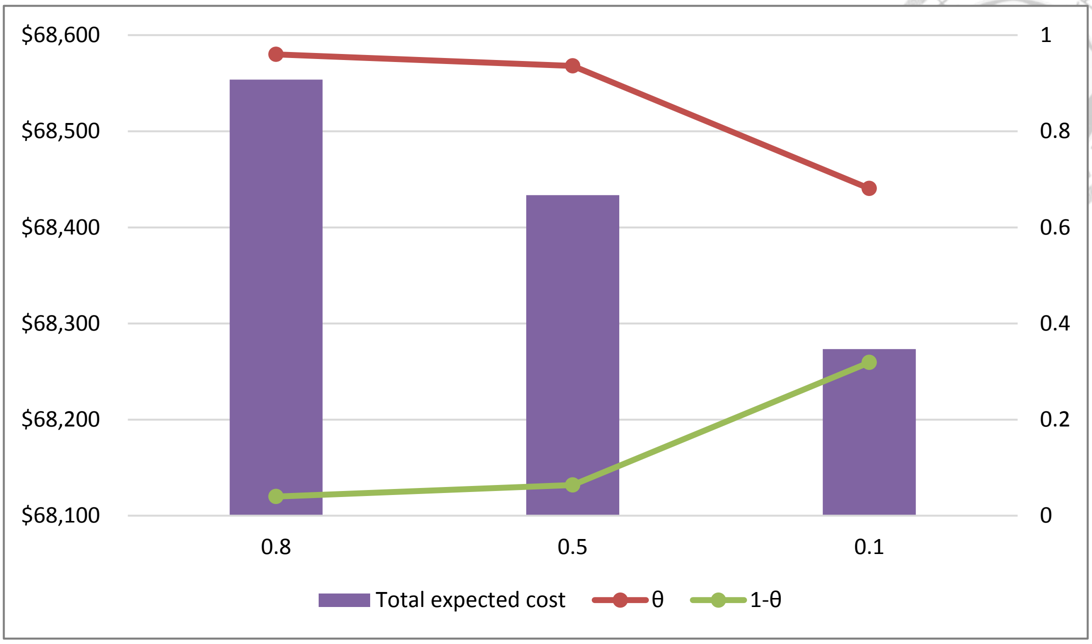


Figure 4.2 The optimal solution under different expected disruption level

From Table 4.4 and Figure 4.2, we can know that as possible disruption level decreases, the proportion of ordering from backup supplier is also decreasing as well as expected working inventory cost. The decreasing of expected cost is predictable because most of order quantity can be ordered from much cheaper primary supplier, but the results of our decision variable are very interesting. As possible disruption level decreases, the proportion of ordering from backup supplier θ decreases, which means the proportion of reserving additional safety stock 1-θ increases. In Table 4.1, as expected disruption level decreases 87.5% $\left(\frac{10\%-80\%}{80\%} * 100\%\right)$, from 80% to 10%, the proportion that retailer should use backup supplier to fulfill unavailable order quantity of primary supplier also decreases 29.1% $\left(\frac{0.681-0.960}{0.960} * 100\%\right)$ and the proportion of additional safety stock increases 7 times $\left(\frac{0.319-0.04}{0.04} * 100\%\right)$ from 0.04. Therefore, this study can conclude that when a downstream firm can ensure its possible disruption level of primary supplier is small, it should distribute more proportion at additional safety stock and do not have to count entirely on backup supplier. Besides, this result is reasonable because if the decision maker is risk avoidance, he/she will definitely want to have more parts of possible unavailable order quantity under his/her control, which can be applied in the form of reserving additional safety stock, this model can ensure retailers get their optimal solutions based on their characteristics.

4.2 Verification of the Model

In this section, this study wants to verify our model to see whether the decision variable θ is truly the optimal solution with the lowest working inventory cost. This study will also use parameters presented above and apply trial and error method to find out the optimal solution of θ. As for disruption level, in here, this study will just use 80% as a parameter of expected disruption level to simplify the verification.

To verify our model, this study puts all parameters into the objective function and then putting numbers on θ from 0 to 1, which can also give us numbers that are related to θ. After that, this study can have the expected working inventory cost of each θ, and the outcomes are shown in Table 4.5.

Table 4.5 The analysis of verification by trial and error method

Proportion of backup supplier	**Expected cost (US$)**	**Difference from the optimal solution (US$)**
θ = 0.960	**$68,553.7**	**Optimal Solution**
θ = 0	$69,089.7	$536.0
θ = 0.55	$68,774.7	$221.0
θ = 0.6	$68,746.0	$192.3
θ = 0.65	$68,717.4	$163.7
θ = 0.7	$68,688.7	$135.0
θ = 0.75	$68,660.1	$106.4
θ = 0.8	$68,631.4	$77.7
θ = 0.85	$68,602.9	$49.2
θ = 0.9	$68,575.0	$21.3
θ = 0.95	$68,554.7	$0.97
θ = 1	$68,579.5	$25.8

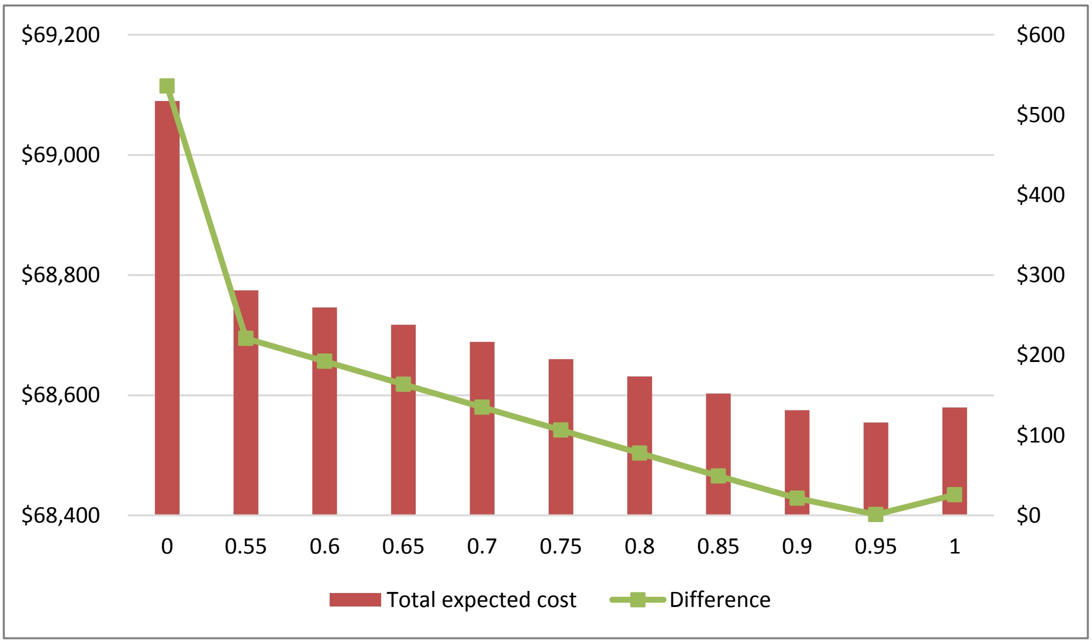


Figure 4.3 The analysis of verification by trial and error method

From Table 4.5 and Figure 4.3, this study can know that when the expected disruption level is 80%, the expected cost is in the interval of $68,554 and $69,090. When θ = 0, the expected cost is \$69,089.7. Along with the gradually increasing θ, the expected cost becomes less and less. And then from the point of 0.95, it stars to increase. Hence, this study can realize that the optimal solution of θ should be nearby 0.95. This conclusion matches the optimal solution of θ that this study found out in last section, which is θ = 0.960. Furthermore, because all numbers of θ above have positive differences from the expected cost of optimal θ, this study can ensure that when θ = 0.960, there is the lowest working inventory cost. Therefore, because the verification of our model, this study can guarantee that the optimal solution resulting from our model is definitely current and can obtain the lowest expected working inventory cost, as a consequence, decision makers can use our model to decide the proportions of their mitigation strategies without any consideration.

4.3 Sensitivity Analysis

In this section, this study will do sensitivity analyses on some parameters which are related to the objective function and decision variable. And this study predicts that these parameters will have influence on both outcomes of objective function and decision variable. From formula (5) back in Chapter 3, we know that all kinds of cost would affect the expected cost, the objective function, and from formula (7) and (11), this study understands that the procurement cost of each supplier C_p and C_b, the holding cost

h and the shortage cost p would also have influence on decision variable since θ would be affected by $\Phi(Z_r)$. Therefore, in this section, this study will use these three kinds of cost to run sensitivity analysis to see its influence on θ and $\mathrm{E}[C(\theta, Z)]$.

4.3.1 Price difference of two suppliers $(\mathrm{C_b} - \mathrm{C_p})$

From previous introduction, this study knows that the price difference of two suppliers would affect both expected cost and decision variable. In addition, as this study has discussed before when this study tried to put numbers on parameters, because the price difference of two suppliers has certain relationship with the holding cost, this study concludes that the price range of backup supplier should be from \$6 to \$11.57 per unit. Hence, this study will use this range of price as the procurement cost of backup supplier C_b to run sensitivity analysis of $C_b - C_p$. This study will just use 80% as a parameter of expected disruption level to simplify the analysis. This study shows the results in Table 4.6 below.

Table 4.6 Sensitivity analysis of price difference of two suppliers

Procurement cost of backup supplier (US\$)	**Price difference from C_p (US\$)**	**Proportion of backup supplier**	**Proportion of additional safety stock**	**Expected cost (US\$)**
\$6	\$0	0.973	0.027	\$68,243.9
\$7	\$1	0.967	0.033	\$68,399.3
\$8	\$2	0.960	0.040	\$68,553.7
\$9	\$3	0.951	0.049	\$68,706.9
\$10	\$4	0.939	0.061	\$68,858.4
\$11	\$5	0.915	0.085	\$69,007.3

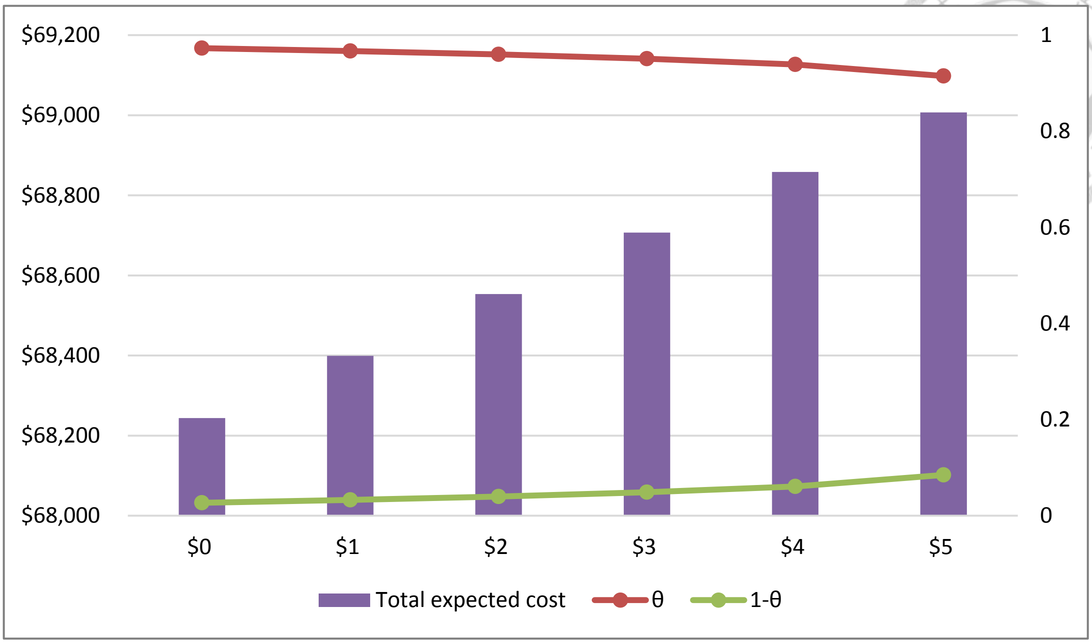


Figure 4.4 Sensitivity analysis of price difference of two suppliers

From Table 4.6 and Figure 4.4, this study can observe that when the procurement cost of backup supplier gradually increases, expected working inventory cost will also increase, which makes sense because the retailer whose backup supplier is more expensive has to pay more than the retailer who owns cheaper backup supplier. When the price difference changes from \$0 to \$5, the expected cost increases 1.12% $\left(\frac{\$69{,}007.3-\$68{,}243.9}{\$68{,}243.9} * 100\%\right)$. As for proportions of backup supplier and additional safety stock, when the price difference increases from \$0 to \$5, proportion of backup supplier decreases 5.96% $\left(\frac{0.915-0.973}{0.973} * 100\%\right)$; on the other hand, under the same circumstance, proportion of additional safety stock will increase 214.81% $\left(\frac{0.085-0.027}{0.027} * 100\%\right)$. This results tell us that when the procurement cost of backup supplier becomes more and more expensive, the retailer should transfer some of its proportion of unavailable order quantity, which used to be ordering from backup supplier, to the mitigation strategy of reserving additional safety stock, such as our example, the percentage of using additional safety stock increases more than 2 times. In addition, the reason why the expected cost only increases 1.12% is exactly because of the transferring of our using percentage of mitigation strategies. When the procurement cost of backup supplier becomes more expensive, this study will pre-reserve more parts of unavailable order quantity on additional safety stock instead of ordering from expensive backup supplier; thus, thanks to relatively cheaper holding cost of additional safety stock, our expected cost will not increase drastically.

4.3.2 Holding cost（h）

This study has introduced that the objective function and decision variable will also be affected by holding cost, so in this section, this study will change the parameter of holding cost to run the sensitivity analysis and wish to find out some insights. Before doing sensitivity analysis, this study has to clarify the relationship between the price difference of two suppliers and the holding cost again. Because according to formula (11), this study knows that under the circumstance that the price difference of two suppliers is $2, the holding cost should be larger than $0.011. In addition, because the decision variable θ could not exceed 1, the holding cost should be smaller than $0.19.

Therefore, the range of holding cost should be from $0.011 to $0.19. And there is one thing this study should declare in here is that in this sensitivity analysis, our order quantity *Q* will be changed as long as the holding cost changes. The reason why this study does not fix the quantity of *Q* is because in our model, *Q* is predetermined by holding cost *h*, the way this study applies *Q* that follows with *h* seems to be a more reasonable choice. Besides, in this analysis, this study will also use 80% as a parameter of expected disruption level for simplification. Our results are as below in Table 4.7.

Table 4.7 Sensitivity analysis of holding cost

Holding cost (US$)	**Proportion of backup supplier**	**Proportion of additional safety stock**	**Expected cost (US$)**
$0.011	0.928	0.072	$67,710.0
$0.03	0.960	0.040	$68,553.7
$0.05	0.965	0.035	$69,296.6
$0.07	0.969	0.031	$69,945.8
$0.09	0.974	0.026	$70,533.5
$0.10	0.976	0.024	$70,810.0
$0.19	0.998	0.002	$72,974.1

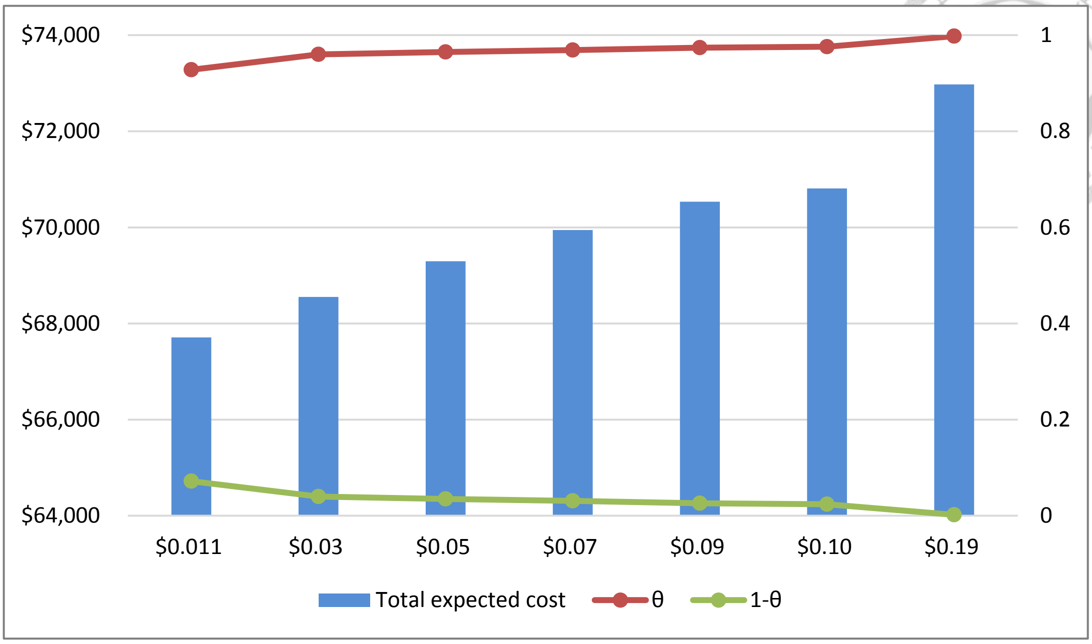


Figure 4.5 Sensitivity analysis of holding cost

From Table 4.7 and Figure 4.5, this study can observe that as holding cost becomes expensive gradually, the expected working inventory cost also becomes more and more, which is reasonable because the retailer whose holding cost is more expensive will have to spend more on its total cost than the retailer who has cheaper holding cost. When the holding cost increases 1627.27% $\left(\frac{\$0.19-\$0.011}{\$0.011} * 100\%\right)$, from \$0.011 to \$0.19, the expected cost increases 7.77% $\left(\frac{\$72{,}974.1-\$67{,}710.0}{\$67{,}710.0} * 100\%\right)$, which is not so drastic compared to the changes of holding cost. As for proportions of backup supplier and additional safety stock, when the holding cost increases 1627.27%, proportion of backup supplier increases 7.54% $\left(\frac{0.998-0.928}{0.928} * 100\%\right)$; on the other hand, under the same circumstance, proportion of additional safety stock decreases 97.22% $\left(\frac{0.002-0.072}{0.072} * 100\%\right)$. From this result, this study can conclude that when the retailer has more expensive holding cost, its proportion of reserving additional safety stock should be less than the retailer who has cheaper holding cost. Besides, the reason why the expected cost only increases 7.77% is because of the transferring of these two mitigation strategies. When holding cost per unit per day becomes more and more expensive, the relatively cheaper procurement cost of backup supplier will replace expensive holding cost to become the most parts of mitigation strategy to achieve our objective function, the lowest working inventory cost. Therefore, as we can see in Table 4.7, when holding cost is $0.19, the proportion of backup supplier is almost nearly 100%; on the other hand, the proportion of additional safety stock is close to 0%, and under this distribution of mitigation strategies, the expected cost can be the lowest and will not have a huge difference with the lowest holding cost's expected cost.

4.3.3 Shortage cost（p）

Shortage cost is also one of parameters that would influence the objective function and decision variable; thus, in this section, this study will use shortage cost to run sensitivity analysis. This study will change the value of shortage cost in a certain range and then to illustrate some insights resulting from this sensitivity analysis. As this study mentioned before, like the situation of holding cost h, because order quantity Q is also predetermined by shortage cost p, Q will change along with p when this study does sensitivity analysis in order to present realistic and reasonable situations. Besides, because the decision variable θ should smaller than 1, through computation, this study finds out that the shortage cost should larger than $2.68. Hence, in sensitivity analysis, this study starts at $2.68 as the shortage cost. As for disruption level, in here, this study will just use 80% as a parameter of expected disruption level for simplification. This study shows the results as below in Table 4.8.

Table 4.8 Sensitivity analysis of shortage cost

Shortage cost (US$)	**Proportion of backup supplier**	**Proportion of additional safety stock**	**Expected cost (US$)**
$2.68	0.99996	0.00004	$68,487.3
$5	0.980	0.020	$68,511.5
$10	0.960	0.040	$68,553.7
$50	0.920	0.080	$68,834.4
$100	0.905	0.095	$69,167.9
$200	0.891	0.109	$69,826.4

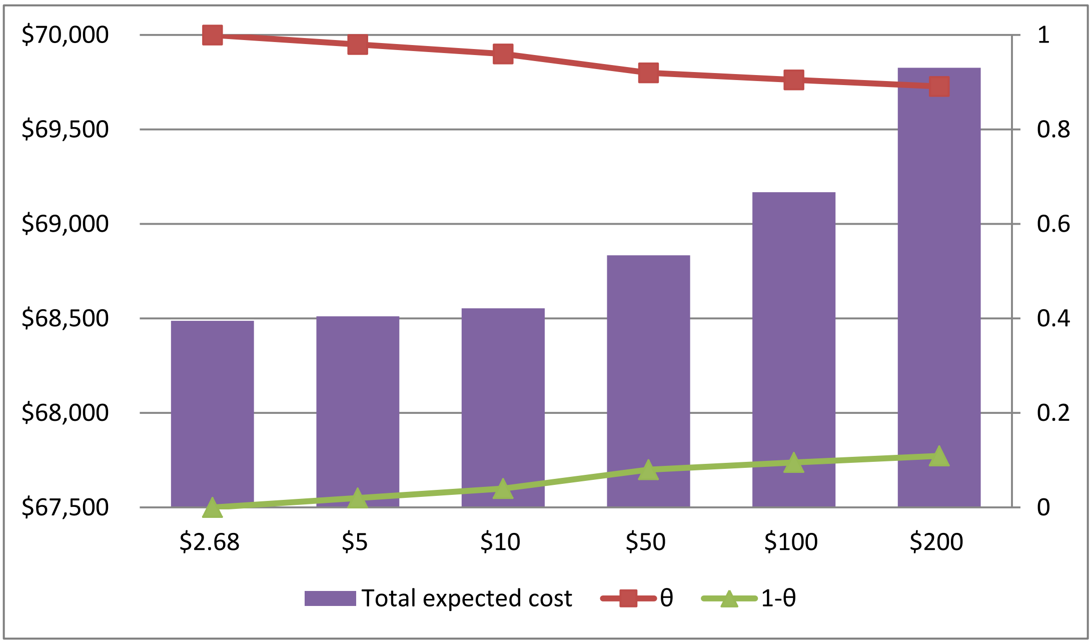


Figure 4.6 Sensitivity analysis of shortage cost

From Table 4.8 and Figure 4.6, this study can observe that as shortage cost becomes more and more expensive gradually, the expected working inventory cost also increases progressively. This conclusion seems reasonable because the retailer has to pay more on total cost along with its increasing shortage cost. When the shortage cost increases 7362.69% $\left(\frac{\$200-\$2.68}{\$2.68} * 100\%\right)$, from \$2.68 to \$200, the expected cost only increases 1.96% $\left(\frac{\$69{,}826.4-\$68{,}487.3}{\$68{,}487.3} * 100\%\right)$, which is relatively small amount compared to the change of shortage cost. As for proportions of backup supplier and additional safety stock, when the shortage cost increases 7362.69%, proportion of backup supplier decreases 10.9% $\left(\frac{0.891-0.99996}{0.99996} * 100\%\right)$; on the other hand, proportion of additional safety stock increases 2724 times $\left(\frac{0.109-0.00004}{0.00004} * 100\%\right)$ under the same circumstance. According to this result, this study can conclude that for the retailer whose shortage cost is costlier, its proportion of additional safety stock should be more than the retailer who has cheaper shortage cost. In other words, when shortage cost becomes costlier and costlier, the retailer should distribute more parts of mitigation strategy on reserving additional safety stock instead of ordering from backup supplier. This finding sounds valid because the basic concept of safety stock is to prevent the possibility of stockout. When we reserve more safety stock, the possibility of stockout can be avoided automatically; therefore, we do not have to pay any shortage cost as long as we have prepared enough safety stock to satisfy customer's requirements. When there is no chance to pay any shortage cost, the expected cost will not be affected by shortage cost, so the result of expected cost will not increase drastically as the change of shortage cost.

4.3.4 Brief summary of sensitivity analysis

In section 4.3, this study has done sensitivity analyses on price difference of two suppliers $C_b - C_p$, holding cost h, and shortage cost p. This study summarizes some findings below to give clearer ideas about these analyses.

(1) When procurement costs of primary supplier and backup supplier have huge price difference, retailer should increase the proportion of additional safety stock and decrease the proportion of backup supplier.

(2) When holding cost is relatively more expensive than other retailers', the retailer should decrease the proportion of additional safety stock and increase the proportion of backup supplier.

(3) When shortage cost is relatively costlier than other costs of retailer, the retailer should increase the proportion of additional safety stock and decrease the proportion of backup supplier, so the increasing additional safety stock can compensate the demands coming from customers.

4.4 Scenario Analysis

In this section, this study will do scenario analyses about two extreme situations to see what the distribution of our two mitigation strategies will be when under such extreme situations. This study wants to see what the objective function and decision variable will be when the retailer is under 100% disruption level of primary supplier and extremely small disruption level of primary supplier. Therefore, this study will set ω_i equals to 100% and extremely small percent, and then running scenario analyses to see its influence on θ and $\mathrm{E}[C(\theta, Z)]$.

4.4.1 Completely disruption at primary supplier

In this section, our scenario is that the retailer's primary supplier is under 100% disruption level, which means primary supplier cannot deliver any order quantity Q to retailer at all, so this study will set ω_i equals 1 and to see what the results of expected cost, proportion of backup supplier and proportion of additional safety stock will be. Other parameters are equal to Table 4.1 and Table 4.2. The results are in Table 4.9.

Table 4.9 Scenario analysis under 100% disruption level

Disruption level	**Proportion of backup supplier**	**Proportion of additional safety stock**	**Expected cost (US$)**
100%	0.968	0.032	$68,633.8

From Table 4.9, this study can understand that when retailer may face 100% disruption level of its primary supplier, it should distribute most parts of mitigation strategy on ordering from backup supplier and just reserve few amount of additional safety stock as its mitigation strategy. Almost 97% of unavailable order quantity should order from backup supplier; on the other hand, only 3% of unavailable order quantity will be compensated by reserved additional safety stock.

4.4.2 Tiny disruption at primary supplier

After understanding the outcomes of totally disruption, this study also wants to run a scenario analysis on the situation of extremely small disruption. Therefore, our scenario in this section is that the retailer may face only a tiny disruption level at primary supplier, and this study wants to find out what the distribution of its mitigation strategies and expected working inventory cost will be when under this tiny disruption level. There is one thing important that this study should mention in here is that the purpose of this model is to find out the optimal distribution of two mitigation strategies; thus, this study has to make sure that no matter what, our decision variable θ should always bigger than 0, and by computation, this study finds out that the disruption level cannot be smaller than 3.2%, so this study will use 3.5% as disruption level at primary supplier in our scenario analysis. Other parameters are equal to Table 4.1 and Table 4.2. The results are shown below in Table 4.10.

Table 4.10 Scenario analysis under 3.5% disruption level

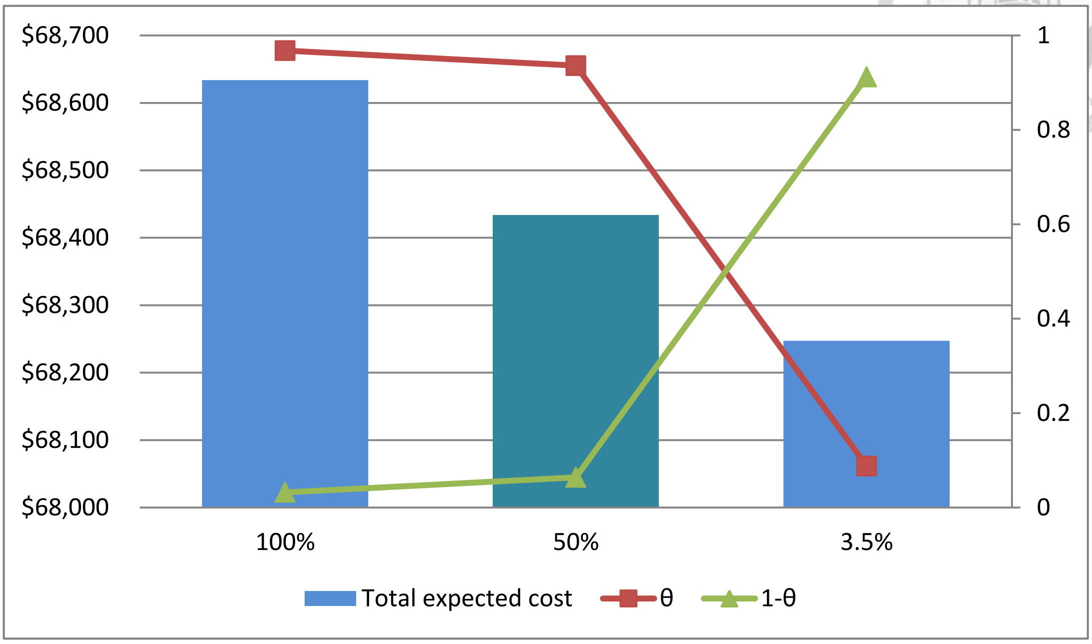
Disruption level	**Proportion of backup supplier**	**Proportion of additional safety stock**	**Expected cost (US$)**
3.5%	0.088	0.912	$68,247.2

From Table 4.10, this study can understand that when the possible disruption level which the retailer may face is very small, the retailer should distribute most parts of mitigation strategy on reserving additional safety stock and just order few amount of unavailable order quantity from backup supplier. Over 91% of unavailable order quantity should be reserved by additional safety stock; on the other hand, only about 9% of unavailable order quantity will be fulfilled by ordering from backup supplier.

4.4.3 Comparison between scenarios

This study puts the results of Table 4.9 and Table 4.10 together in Figure 4.7. Besides, this study also puts semi-disruption level 50% in Figure 4.7 as reference.

Figure 4.7 Scenario analyses of two situations



From Table 4.9, Table 4.10 and Figure 4.7, when disruption level decreases 96.5% $\left(\frac{3.5\%-100\%}{100\%}*100\%\right)$, the proportions of backup supplier and additional safety stock also have huge changes, which decreases 90.91% $\left(\frac{0.088-0.968}{0.968}*100\%\right)$ and increases 2750% $\left(\frac{0.912-0.032}{0.032}*100\%\right)$ respectively, and the expected cost also decreases 0.56% $\left(\frac{\$68{,}247.2-\$68{,}633.8}{\$68{,}633.8}*100\%\right)$. Compared to huge differences of disruption level and proportions of two mitigation strategies, the change of expected cost is not so drastic. This result proves that by applying our model, on matter in what kind of situation, the retailer can obtain the optimal solution and do not have to worry about there will be a huge difference on its cost even under totally different disruption level. Therefore, this shows that our model can give decision makers a proper advice about how to distribute their mitigation strategies and also ensure that their working inventory cost resulting from following this model will be in a reasonable range.

4.4.4 Brief summary of scenario analysis

In section 4.4, this study has done scenario analyses under two extremely value of disruption level. One is 100% totally disruption and the other one is 3.5% tiny disruption level. This study summarizes some findings below to give clearer ideas about these two analyses.

(1) When disruption level may be very huge, retailer should increase the proportion of backup supplier and decrease the proportion of additional safety stock.

(2) When disruption level may be very small, retailer should increase the proportion of additional safety stock and decrease the proportion of backup supplier.

(3) No matter what disruption level is, the expected cost will not change too much.

4.5 Chapter Summarization

In conclusion, this study has done several analyses in this chapter. First, this study applies some parameters to give examples about how to use our model in real situation. Secondly, this study adjusts our decision variable away from its optimal solution to verify the validity of our model. And thirdly, this study uses three kinds of costs to run sensitivity analyses and observe their relation with decision variable. Finally, the last but not the least, this study runs scenario analyses to see what the objective function and decision variable will be when under the best or the worst disruption level. From these analyses, this study finds out some insights and hopes these findings can provide decision makers guidance about how to distribute their mitigation strategies.

Chapter 5 Conclusions

5.1 Conclusion

In recent year, as international business becomes more and more active, supply chain also becomes more and more complex. And the severity and frequency of supply chain risk seem to be increasing as well. Therefore, mitigation approaches for these supply chin risk are very urgent and important.

In our research, this study considers a stochastic continuous-review inventory model for a problem with a single retailer and two suppliers, in which the primary supplier may be randomly disrupted. This study studies properties of the expected working inventory cost function and suggest a numerical solution algorithm to obtain the optimal proportions of backup supplier and additional safety stock that retailer should apply when distributing its mitigation strategies. In addition, this study also finds out a constraint in our model that this study should pay attention to when applying this model into use. Furthermore, in order to be more reality, this study also takes possible disruption level into consideration to see what outcomes will be for the objective function and decision variable, and indeed, this study really finds out the differences under different possible disruption levels.

The computational experiments in our research show many findings from our mathematical model. First, certain types of cost would influence the distribution of our two mitigation strategies. If price difference of procurement cost of two suppliers and shortage cost are relatively expensive compared to other costs, decision maker should distribute more parts on additional safety stock as its mitigation strategy than those retailers who have cheaper procurement cost on backup supplier and shortage cost. On the other hand, if holding cost is relatively costly compared to other costs, contrarily, decision maker should distribute more parts on ordering from backup supplier than those retailers whose holding cost is much cheaper. This finding also matches the suggestions of Chopra and Sodhi (2004), which is using redundant suppliers more when holding cost of product is high. In addition, different disruption levels also have impact on the distribution of our two mitigation strategies. If the disruption level at primary supplier that a downstream decision maker may face is huge, decision make should distribute more parts of its mitigation strategy on ordering from backup supplier; on the other hand, if the possible disruption level at primary supplier is tiny, the downstream decision maker should distribute more parts of its mitigation strategy on reserving additional safety stock. The optimal solutions are totally different under different possible disruption levels. This finding can be very useful because, according to this conclusion, downstream decision maker can understand what its optimal strategy will be and from this optimal strategy, decision maker can know what kind of related cost is a potential opportunity to reduce company's total working inventory cost and then taking action to figure out solutions that can decrease related costs.

From the illustration this study just pointed out, we can know that our findings also provide management implication. Decision maker can base on its optimal solution to figure out what the key cost is and try to improve this cost so as to reduce its total cost. Our research also provides a proof showing that applying two mitigation strategies together with the optimal solution can really benefit downstream retailers. Furthermore, decision maker does not have to worry about a massive difference on its total cost even if there are some changes as long as following our model since our model will provide the best distribution policy on these two mitigation strategies.

5.2 Prospect

Our research is just a preliminary research about supply chain disruption risk management. There are still something that can be extended in at least three aspects. First, the model proposed in this research is using additional safety stock and backup supplier as mitigation strategies, but there are many other mitigation approaches can be used such as pooling demand. Thus, these mitigation strategies can also be alternatives to our model and there may be some insights as well. Secondly, in our model, this study assumes that the backup supplier does not have time constraint and capacity constraint, but in reality, backup supplier cannot be that flexible, which means there may be constraints on these two key capabilities. Hence, this study suggests that later research can base on our model and add these two key capabilities of backup supplier into consideration to make this model more reality. Lastly, there are some researches also considering disruptions at the retailer such as Qi, Shen & Snyder, 2009, so this study also suggests that later research can add this consideration into our model, considering disruption at primary supplier and retailer together, to make this model become more useful and diverse.

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