Managing procurement costs and risks in supply chain networks

Hong, Zhen

2014

Hong, Z. (2014). Managing procurement costs and risks in supply chain networks. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/60682>

<https://doi.org/10.32657/10356/60682>

**MANAGING PROCUREMENT COSTS AND RISKS IN
SUPPLY CHAIN NETWORKS**

HONG ZHEN

School of Mechanical and Aerospace Engineering

A thesis submitted to the

Nanyang Technological University

in partial fulfillment of the requirement for the degree of

Doctor of Philosophy

2014

Abstract

The industrial globalization trend makes the supply chain a more and more complicated and volatile part in the manufacturing industries. Procurement planning, which is an important activity of supply chain management, should be formulated by considering both operational risk and disruptive risk in the dynamic business environment. Therefore, procurement decision making under uncertainty has attracted considerable attention in both academia and industry.

There are several challenges faced by enterprises and researches in this area, one of which is how to use reactive supply (i.e. spot market) to reduce yield risk taking into account interrelated uncertainties in demand, spot price and yield. Moreover, how to best utilize supply diversification to reduce yield and demand uncertainties is also a sophisticated challenge. A third challenge is the lead time uncertainty management, which involves whether the purchasing company should control the delivery of forward contract items by itself or let the suppliers be responsible for the delivery.

To address these challenges, a comprehensive study on how to make optimal procurement decisions under yield and demand uncertainty in the presence of spot market is conducted in this thesis, with the objective to reduce the impact of risks in procurement. The uncertainties of yields, spot prices and demand, and the correlations among them are taken into consideration when designing procurement plans. This thesis has evaluated the effectiveness of dealing with uncertain supply using the spot market along with the contract supplier and has modeled the dependences among all the potential uncertainties. This research also seeks high expected profits without overlooking the associated

variances. Based on that, mathematical models based on a mean-variance framework are developed to obtain analytical solutions, with the risk sensitivity analysis on several key factors. The analytical expression to determine the optimal order quantity is obtained under the most general situations where commodities can be both bought and sold via the spot market. Some properties are derived to provide useful managerial insights. In addition, reference scenarios, such as pure contract (PC) sourcing and the spot market restricted for buying only (BO) or selling only (SO), are included for comparison purposes.

Out of the research studies, we have achieved some accomplishments: Firstly, a novel procurement risk management (PRM) framework is proposed to help buyers make optimal ordering and delivery arrangement decisions. Secondly, it is proved that the adoption of reactive supply (e.g. spot market) could greatly increase profits and control risks within a certain level. Last but not least, the interrelated demand, spot price and yield risks in this complicated problem are modeled with closed form result obtained.

Real-world industrial case studies are also conducted to complete the research work that we have undergone. During the procurement strategy design for a semi-conductor manufacturing company, optimal procurement and delivery decisions are made with the help of the proposed integrated PRM framework. We believe that these contributions would sustainably benefit the industries with superior supply chain management techniques backed by the strong theoretical foundation.

Acknowledgments

Special appreciation would be given to my PhD supervisors Dr. Carman Lee Ka Man and Dr. Nie Xiaofeng. They have broad and rich knowledge in the area of supply chain management, and are also very generous and helpful. Opinions from them are very useful which successfully guide my way toward a good researcher.

The author would also like to thank Dr. Rajesh Piplani, Dr. Wu Zhang and Dr. Mao Jianfeng for their valuable advices to my confirmation report.

I am also grateful to all staffs in TRIO-TECH International Pte Ltd Singapore for their patient guidance during my industrial attachment, especially to:

- Mr. Eric Ling; department head of procurement and logistics department; he taught me management knowledge and showed me how to analyze a market trend;
- Ms. Joana Tan; senior procurement officer, her professional attitude and rich knowledge give me a deep impression;

I also want to thank all my friends in the lab for the precious time that we have spent together during my PhD study.

Last but not least, great thanks to my family members for always being my joy and worry partners.

Table of Contents

ABSTRACT	I
ACKNOWLEDGMENTS	III
TABLE OF CONTENTS	IV
LIST OF TABLES	IX
LIST OF FIGURES	X
LIST OF ABBREVIATIONS	XII
LIST OF PUBLICATIONS	XIII
CHAPTER 1 INTRODUCTION	1
1.1 Background	1
1.1.1 Challenges in procurement via only forward contracts	2
1.1.2 Opportunities from reactive sourcing	4
1.2 Research motivation	5
1.2.1 The importance of PRM	5
1.2.2 The complexity of PRM	9
1.3 Research scope	11
1.4 Research objectives	11

1.5	Organization of this thesis	12
CHAPTER 2 LITERATURE REVIEW		14
2.1	Review methodology	14
2.1.1	Procurement risk taxonomy and scope of this review	14
2.1.2	Supply chain risk management framework	16
2.2	Classification of PRM under uncertainty	19
2.2.1	Uncertain demand	19
2.2.2	Uncertain price	22
2.2.3	Uncertain yield	23
2.2.4	Uncertain lead time	24
2.2.5	Disruption risks	25
2.3	PRM strategies under uncertainty	25
2.3.1	Supplier diversification	26
2.3.2	Back up sourcing.....	31
2.3.3	Flexible contract design	34
2.3.4	Other strategies	36
2.4	PRM under dependent risks in the presence of spot market	39
2.4.1	Proactive and reactive purchasing planning under dependent demand, price and yield risks	39
2.4.2	An integrated PRM framework in the presence of spot market	41
2.5	Research gaps.....	43
2.6	Summary	44
CHAPTER 3 PROACTIVE AND REACTIVE PURCHASING PLANNING UNDER DEPENDENT DEMAND, PRICE AND YIELD RISKS.....		45

3.1 Problem background	46
3.2 Problem formulation and solution approach	47
3.2.1 BS model.....	48
3.2.2 Other models	53
3.3 Computational study	55
3.3.1 Effect of risk aversion	56
3.3.2 Effect of yield COVs.....	57
3.3.3 Effect of spot price COVs	58
3.3.4 Effect of demand COVs	58
3.3.5 Effect of demand, yield and price correlations.....	59
3.3.6 Multiple parameterized simulations	61
3.4 Summary	62
 CHAPTER 4 A DECISION SUPPORT SYSTEM FOR PROCUREMENT RISK MANAGEMENT IN THE PRESENCE OF SPOT MARKET	 64
4.1 Introduction.....	64
4.1.1 The proposed PRM decision support system	65
4.1.2 Research implications	66
4.2 Procurement risk identification.....	68
4.2.1 Defining the SCR-FMEA risk identification methodology.....	69
4.2.2 The designing of SCR-FMEA.....	70
4.2.3 Critical procurement risks ranking using RPN map.....	72
4.3 Procurement risk assessment.....	73
4.3.1 Supplier risk assessment based on Profit-SaR matrix	75
4.3.2 Delivery risk assessment	80

4.4 Procurement risk mitigation	82
4.4.1 Supplier diversification for the optimal ordering decision making	83
4.4.2 Reactive sourcing for the optimal ordering decision making.....	86
4.4.3 Comparison analysis for delivery arrangement decision making.....	87
4.5 Procurement risk monitoring	88
4.6 Summary	88
 CHAPTER 5 CASE STUDY	 90
 5.1 The Procurement business process.....	 90
 5.2 Procurement risks in the semiconductor industry	 93
 5.3 Case study scenario one for optimal ordering decision	 94
5.3.1 Data for the case study	95
5.3.2 Optimization model for the case study.....	98
5.3.3 Result analysis	99
 5.4 Case study scenario two for delivery arrangement.....	 104
5.4.1 Data for the case study	106
5.4.2 Simulation model for the case study	107
5.4.3 Result analysis	111
 5.5 Summary	 116
 CHAPTER 6 CONCLUSIONS.....	 117
 6.1 Summary of the research	 117
 6.2 Contributions of this research study	 121

6.3 Limitations and future work.....	122
REFERENCES.....	125

List of Tables

Table 2.1: Risks in procurement	16
Table 2.2: Distribution of selected papers related to PRM.....	18
Table 2.3: Classification of research papers according to specific procurement risk.....	21
Table 2.4: An overview of PRM models with supplier diversification strategy	29
Table 2.5: An overview of PRM models with back up sourcing strategy	32
Table 2.6: An overview of PRM models with flexible contract design	36
Table 3.1: Summary of parameter values	55
Table 3.2: Correlation coefficient parameter values and results.....	60
Table 3.3: Comparison analysis of two groups.....	62
Table 4.1: Risk probability factors, impact factors and detection factors in SCR-FMEA .	74
Table 4.2: Available distributions in solver sdk platform	77
Table 4.3: Delivery outsourcing risk management plan	88
Table 5.1: Major procurement risks and consequences in the semiconductor industry	94
Table 5.2: Data of the case company	97
Table 5.3: The simulation result of the Profit-SaR map	100
Table 5.4: Optimal order allocation among the supplier pool	102
Table 5.5: Input summary for lead time information.....	108
Table 5.6: Input summary for cost information	109
Table 5.7: Output summary of uncertain lead time	113
Table 5.8: Output summary of uncertain cost.....	114

List of Figures

Figure 1.1: Reactive sourcing using spot market DRAMeXchange.....	4
Figure 1.2: The structure of the thesis	13
Figure 2.1: Literature search flowchart.....	17
Figure 2.2: PRM strategy	26
Figure 3.1: Comparisons under different risk aversion settings	56
Figure 3.2: Comparisons under different yield COVs	57
Figure 3.3: Comparisons under different spot price COVs	58
Figure 3.4: Comparisons under different demand COVs	59
Figure 4.1: Framework of the integrated PRM solution	67
Figure 4.2: Multiple suppliers sourcing in the presence of spot market under uncertainties	69
Figure 4.3: Relation of risk event and its risk score	71
Figure 4.4: Headings of a sample standard FMEA vs. designed SCR-FMEA	71
Figure 4.5: Risk map of RPN against risk score	75
Figure 4.6: Profit-SaR Matrix	79
Figure 4.7: Risk assessment model on spreadsheet	82
Figure 4.8: The purchasing process in a single period	83
Figure 5.1: A common procurement workflow in the procurement department	91

Figure 5.2: A forward contract example	92
Figure 5.3: The decision support system in the case study	101
Figure 5.4: High-low-average demand and the ordered quantity from selected suppliers	105
Figure 5.5: Comparisons between ordering average quantity and optimal quantity	105
Figure 5.6: Simulation of risk assessment for case study	111
Figure 5.7: Monte Carlo simulation results for before and after outsourcing	112

List of Abbreviations

A-EPSaR:	Expected Profit – Supply at Risk
A-RDSS:	Remove Dominated Supplier from Supplier Pool
AHP:	Analytic Hierarchy Process
B2B:	Business-to-Business
BO:	Buying Only
BS:	Buying and Selling
COV:	Coefficient of Variation
EPGR:	Expected Profit Gap Rate
EPOA:	Expected Profit - Order Average
EPOO:	Expected Profit - Order Optimal
FMEA:	Failure Mode and Effects Analysis
OVOA:	Objective Value - Order Average
OVOO:	Objective Value - Order Optimal
PC:	Pure Contract
PPRM:	Proactive Procurement Risk Management
PRM:	Procurement Risk Management
PSOA:	Profit SD - Order Average
PSOO:	Profit SD - Order Optimal
PVGR:	Profit Variance Gap Rate
QGR:	Quantity Gap Rate
RPN:	Risk Priority Number
RPRM:	Reactive Procurement Risk Management
SCR-FMEA:	Supply Chain Risk – Failure Mode and Effects Analysis
SO:	Selling Only
SaR:	Supply at Risk
VaR:	Value at Risk

List of Publications

1. Zhen Hong and CKM Lee, 2013. A decision support system for procurement risk management in the presence of spot market. *Decision Support Systems* 55(1):67-78.
2. Zhen Hong, CKM Lee and Xiaofeng Nie, 2013. Proactive and reactive purchasing planning under dependent demand, price and yield risks. *OR Spectrum*.
3. CKM Lee, Yu Ching Yeung and Zhen Hong, 2012. An integrated framework for outsourcing risk management. *Industrial Management and Data Systems* 112(4):541-558.
4. CKM Lee, Yaqiong Lv and Zhen Hong, 2013. Risk modeling and assessment for distributed manufacturing system. *International Journal of Production Research* 51(9):2652-2666.
5. CKM Lee, Yu Ching Yeung, Zhen Hong, 2011. Managing the risks of outsourcing in supply chain networks. *IEEE International Technology Management Conference*. San Jose, 488-494.
6. Zhen Hong, CKM Lee and Xiaofeng Nie, 2011. Optimal procurement strategies under yield uncertainty with spot market. *IEEE International Conference on Quality and Reliability*. Bangkok, Thailand: 355-360
7. Zhen Hong, CKM Lee and KL Choy, 2010. A quality risk model based on supply chain perspective, *SCIMIS*, Hong Kong.

Chapter 1

Introduction

Chapter 1 firstly provides an overview of uncertainties existing in procurement and supply chain industry. Facing these uncertainties, advantages and disadvantages of using only long term contract suppliers (forward contract) are discussed. In order to meet new challenges, buyers are suggested to make use of emerging supply channels, such as spot market. In addition, the risk management of lead time uncertainty for forward contract items delivery is also introduced. Subsequently, the research problems, motivations, objectives and methodology are discussed. Finally, the organization of the thesis is also described.

1.1 Background

Nowadays, enterprises are facing very fierce competitions on price, product quality as well as logistics services. In order to stay competitive and stand a better position, many manufacturing companies choose to focus on the process where their core competency lies in, while sourcing upstream materials globally to achieve lower costs than if they would produce the materials by themselves. This kind of business trend is actually beneficial to all the participants in the supply chain from the efficiency point of view, as each participant, from the upstream to the downstream of this value chain, can now

concentrate on their respective core technology and competency, rendering higher return on their capital investment. And eventually, the overall productivity along this value chain can be improved with reduced cost.

The prices of the benefits brought by this specialization in manufacturing are complications on each stakeholder's supply chain management. As a global trend, the majority of raw materials and components are now manufactured by suppliers at countries with lowest costs, many of which are overseas and hard to monitor. Therefore, supply from these offshore suppliers has inherent uncertainties in supply stability, credibility and delivery punctuality. For example, companies from a large range of industries experienced supply issues from Japan after the earthquake and tsunami in Japan in March, such as Korean shipbuilders, U.S solar power companies and personal computers manufacturers (Kim and Jim, 2011). Another recent case was the autumn floods in Thailand last year; it affected supply of many companies including Honda Motor Co. Ltd, Nissan Motor Co. Ltd and Toyota Motor Corp (Rodd, 2013). In order to stand out in this dynamic and challenging business environment, companies should possess robust and versatile risk management capabilities.

1.1.1 Challenges in procurement via only forward contracts

Traditional arrangement of procuring raw materials is via long term bilateral forward contract, in which the stipulated items are agreed to be delivered sometime in the future with fixed price and quantity, and the associated terms and conditions are negotiable between buyers and suppliers. The characteristics of this kind of procurement/supply mode are: 1) Buyers usually rely on the forward contract as the main source of supply; 2) The lead time of the forward contract, which is the time from signing the contract to

delivering the goods, is usually long, ranging from months to years; and 3) Benefiting from the long lead time, suppliers can safely schedule their production or sourcing plan. Thus suppliers are able to reduce their manufacturing cost and offer low price to buyers (Carrion et al., 2007; Pineda, 2008).

However, due to the intrinsic long lead time in this traditional procurement mode, solely relying on forward contract no longer suffices to meet procurement needs under this dynamic market environment.

First of all, the long lead time of suppliers brings about risks in production yield and delivery lead time for the buyers. Driven by global competition, the buyers tend to choose offshore suppliers with much lower price than domestic suppliers. Therefore, the latency in communication and shipping increases and in turn it renders higher uncertainties in delivery lead time. If the due date approaches, yet the supplier fails to deliver the raw materials and components in a timely manner, the buyers would be trapped in trouble.

Even though the items can be delivered on time by the suppliers, the buyer's production plan may have changed during this long lead time given the dynamic market conditions. If the buyer needs more raw materials than the quantity secured in the forward contract, it would not have enough time to place a second order via forward contract. On the other hand, if the buyer had decided to shrink the production during this period, it may end up receiving and paying for more materials than it actually requires on the due day.

Other than that, there are many more uncertainties in procurement and supply management. Among all these potential risks, Haksöz et al. (2008) conclude that the most essential challenges of procurement are to control the risks in demand, price and breach of contract. Therefore, a reliable supplier and a responsible purchasing team would help to

reduce these uncertainties, thus making the supply more robust. But more importantly, a robust and versatile PRM plan would be vital to mitigate these risks. Some companies have already realized the importance of designing a detailed PRM plan to address the uncertainties in the market. For example, HP has formed a PRM team aiming at reducing procurement risk, which has enabled around \$100 million dollars incremental savings over the past 5 years (Nagali et al., 2008).

1.1.2 Opportunities from reactive sourcing

Although PRM has received considerable attentions from both academic researchers and industry practitioners, there are still many more works and studies to be done, especially with increasing choices of available supply channels. With the rapid development in commodity markets, buyers are provided with more choices to purchase raw materials, components and parts. For example, leveraging on its short lead time, the spot market can be used as a reactive supply to supplement forward contracts. A typical example of using the spot market for reactive sourcing is the famous DRAMexchange on which DRAM/flash memory products are traded daily (as shown in Figure 1.1).

The screenshot shows the DRAMexchange website interface. The top navigation bar includes links for HOME, Market Intelligence, B2B Trading, Weekly Research, SSD ZONE, Market Activity, Price Quotes, Event, Forum, and News. Below the navigation bar, the 'B2B-Trading Gateway' section is highlighted. It contains a registration form with the following fields:

- Name * (First Name, Last Name)
- Business Email *
- Business Phone *
- Company Name *
- Job Title
- City/Country
- Website

Below the form, there is a section for 'Benefits for buyers' and 'Benefits for sellers'.

Benefits for buyers :

- Get the most up to date price quotations through emails and instant messages
- Connect to worldwide suppliers with a simple click of the mouse
- Experience the instant product purchase and delivery service

Benefits for sellers :

- Reach to thousands of potential buyers in buoyant demands worldwide
- Trading products in an efficient manner
- Feel secure as clientele information are kept in a confidential manner

Figure 1.1: Reactive sourcing using spot market DRAMeXchange

In the spot market, the lead time is quite short. Due to the short turnaround time, the price in spot market is usually much higher compared with that of long term forward contract. To make it more complicated, the price in the spot market is also volatile and hard to predict. Nevertheless, spot market is definitely an effective way to do reactive risk management because of its advantage in neglectable lead time (Kawai, 1983; Goel and Gutierrez, 2004; Seifert et al., 2004; Haksöz and Seshadri 2006).

In fact, spot market is studied by many economists for pricing and hedging of commodities (Stoll and Whaley, 1993; Chambers and Bailey, 1996; Routledge et al., 2000). But there are still a lot of works to do for investigating the effect of spot market on supply chain and the trade-offs between the spot market and contract suppliers (Li et al., 2009).

Therefore, the combinatorial use of both Proactive Procurement Risk Management (PPRM) in the form of forward contract and Reactive Procurement Risk Management (RPRM) in the form of spot market enables buyers to tradeoff between cost and lead time, thus offering more reliable and flexible procurement alternatives for the buyers.

1.2 Research motivation

PRM is of great importance and is also a difficult research problem. In this subsection, the significance and the complexity of the problem are described in detail.

1.2.1 The importance of PRM

PRM is of great importance and is crucial to the success of supply management (Porter, 1991; Watts et al., 1995). With the popularity of global sourcing from 1980s, many companies focus on core competency and search for supply overseas (Hätönen and

Eriksson, 2009). For example, Dell purchases the manufacturing of computer components from the low cost countries overseas and focuses on assembling each ordered unit according to a selection of custom options. This kind of business model is good for Dell and other business partners, so that everyone can invest more resources on its core technology and competency. But this brings big challenges for procurement. Indeed, procurement is becoming more and more challenging in this dynamic market environment in terms of supplier risk management (Kraljic, 1983; Li et al., 2009). Nowadays the majority of raw materials and components are manufactured in countries where costs are lower. Overseas business partners and component producers are difficult to be monitored. Therefore, supply from these contract suppliers is hard to be controlled and has different extents of uncertainty. In fact, there are many uncertainties in procurement (Chopra and Sodhi, 2004; Haksöz et al., 2008), such as variable lead time and uncertain demand. Since the lead times of these contracts are usually quite long, the buyer doesn't have enough time to place a second order when the uncertain demand or uncertain yield is realized. Or when the supply is affected by nature disasters, part or all of suppliers' production capability is halted. Some companies have already realized the importance of managing procurement risk. For example, HP has formed a PRM team and enabled \$100 million dollars in accumulative savings over the past 5 years according to Nagali et al. (2008).

In a typical manufacturing company, the main responsibilities of the procurement department include procurement of items requested by production department and arrangement of delivery. The current and emerging challenges of the business environment call for effective solutions for two important problems:

- How can company effectively use spot market to purchase commodities considering all the uncertainties in demand, yield and spot price? and
- How can company efficiently control the lead time uncertainty for forward contract items delivery?

According to McKinsey and CAPS Research, it is important and necessary to utilize spot market for commodity purchasing to supplement long term forward contract. In the presence of spot market, Haksöz et al. (2008) point out that the interrelated demand, spot price and yield uncertainties should be considered. Therefore, a theoretical PRM framework will be helpful to solve both decision making problems of optimal ordering and delivery arrangement.

More specifically, an adequate PRM framework should be able to tackle the following questions:

- **What should company do if there are not enough/more than needed components ordered?** As both demand and yield are uncertain, it is impossible to know beforehand the exact quantities of items required. If the forward contract undersupplies, there is not enough time for the buyer to place a second order of forward contract, considering the long lead time of the commonly used forward contract. On the other hand, if the forward contract oversupplies, it is not wise to keep inventory for high-tech components as the technology is developing very quickly and items that kept in warehouse may depreciate in value quickly. Hence, a good PRM framework should make available flexible and effective solutions to either top-up undersupplied inventories or release oversupplied commodities when necessary.

- **How can company make the order allocation decision under demand and yield uncertainties?** After potential suppliers provide the quotation, procurement staff needs to decide which suppliers to select and how to partition the orders among them. This decision is actually quite difficult given the existence of both internal and external uncertainties. Without a proper quantitative decision support mechanism, the staff would have to make these decisions totally based on personal experiences, which makes it rare to achieve the optimal decision especially for inexperienced personnel. Thus, a good PRM framework should be able to provide systematic and quantitative solutions without too much subjective judgment.
- **How can company incorporate buyers' attitude towards risk to formulate the optimal procurement plan under demand and yield uncertainties?** As the buyer is the decision maker of the procurement plan, his/her risk appetite affects the final decision a lot in a dynamic business environment. A good PRM framework should be able to cater the buyers' risk appetite by allowing adjustment in certain coefficients, and then generate optimal plans accordingly.
- **Whether the delivery should be arranged by the purchasing department or handled by the supplier in an uncertain business environment?** Because the business environment is not static, costs and lead time of delivery also have uncertainties. If the purchasing department arranges the delivery by itself, the cost is usually higher but the lead time control is more reliable. However, if the supplier is asked to be responsible for the delivery, the cost would be lower but the lead time is in less control. An effective PRM framework should provide suggestions on delivery arrangement under different situations.

1.2.2 The complexity of PRM

Supply chain risk management has attracted the attention of both academia and industry. Due to the trend of outsourcing, supply chain structures become more complex and difficult to manage. Dealing with remote suppliers is quite challenging for purchasing departments, as remote suppliers have high levels of delivery uncertainties. Global sourcing is common for enterprises due to the dispersed geographic locations of production facilities and the competitive costs of raw materials.

Apart from prices, Wilson (1994) points out that quality should also be an essential criterion. The emphasis on quality issues increases the awareness of companies to reduce yield uncertainties. There are several facts in industry which show that supply chains are vulnerable and are exposed to yield risks, such as unstable production and unreliable delivery. One typical example is in the agriculture industry, where the harvest of food can be greatly affected by weather which cannot be controlled easily (Erdem and Özekici, 2002). This unpredictable production output results in unreliable supply from the perspective of procurement. In order to provide stable and reliable supply to serve customer demand, successful purchasing plans should take random yields into consideration. Another major uncertainty that companies usually encounter comes from demand. With the increase of product variety and technology improvement, the lifecycles of products are shorter and shorter. Therefore, customer demand becomes more and more unstable (Hazra and Mahadevan, 2009).

In order to provide an efficient reactive supply facing all the above uncertainties, buyers are suggested to use spot market as a reactive supply with the ubiquitous presence of business-to-business (B2B) exchanges and the growing liquidity of spot markets.

Following the business trend, supply chain literature is growing rapidly by presenting models that encompass options to procure from the spot market in addition to regular proactive suppliers (Akella et al., 2001; Golovachkina and Bradley, 2002; Yi and Scheller-Wolf, 2003; Seifert et al., 2004; Mendelson and Tunca, 2007; Inderfurth and Kelle, 2011). In face of uncertain demand and price in spot market, Seifert et al. (2004) try to find out the optimal order quantity from forward contract supplier. Haksöz et al. (2008) suggest that spot market is emerging for a host of commodities, buyers can use it to make up for the lost supply but need to consider demand, spot price and yield uncertainties when making decisions. In order to reduce yield uncertainty, supply diversification is also proposed and studied. Federgruen and Yang (2008) develop a model to configure the supply base and calculate order allocation among suppliers in the presence of yield and demand uncertainties in a single period setting.

However, there is not sufficient quantitative research on how spot market can be used to reduce yield uncertainty, while supply diversification has been widely used for managing yield uncertainty and has been proved as an effective strategy. Therefore, if we combine reactive supply and supply diversification together to mitigate the risks of yield and demand, it should work well even for complicated cases.

Another challenge in this field is that how to manage the interrelated demand, spot price and yield uncertainties as identified by Haksöz et al. (2008). Moreover, procurement decision is also affected by the buyer's risk aversion attitude in the real-world situation, and this factor should also be considered (Seifert et al., 2004). All these challenges and practical problems motivate us to delve into the topic of procurement risk management.

1.3 Research scope

The overall supply chain risk management can be divided into four domains: supply management, product management, demand management and information management. This research focuses on supply management where suitable risk management strategies are applied.

1.4 Research objectives

With both proactive (forward contract) and reactive (spot market) supply sources, the objective of this research is to develop an effective PRM methodology to help make reliable procurement decisions under demand, spot price and yield uncertainties and to minimize the cost while controlling the risks within a certain level. In particular, the optimal order allocation between forward contract and spot market should be achieved as well. If facing multiple forward contract suppliers, optimal suppliers should be selected and order partition among them should also be calculated. Furthermore, the decision support methodology should also be able to help make logistics arrangement decision. A detailed list of important research objectives for optimal ordering and delivery arrangement decision making are summarized, respectively.

Optimal Ordering Decision Making

- To utilize both proactive (contract supplier) and reactive (spot market) strategies to manage the risks of procurement;
- To reduce the risk of oversupplying or undersupplying for using forward contract suppliers only;

- To help the buyer to determine the optimal order allocation among spot market and contract supplier under dependent demand, price and yield risks;
- To utilize supplier diversification and achieve optimal order allocation among multiple suppliers;
- To do risk sensitivity analysis against factors such as yield, demand, spot price and the correlation coefficients among them; and
- To examine the impact of buyer's risk aversion appetite on the procurement decisions under yield uncertainty in the presence of spot market.

Delivery Arrangement Decision Making

- To reduce the overall lead time uncertainty of forward contract procurement.
- To help analyze the risks in different stages of the procurement process.

1.5 Organization of this thesis

As illustrated in Figure 1.2, this thesis consists of six chapters: In Chapter 1, a brief introduction of PRM is provided, including challenges and opportunities of current procurement industry, and the research motivation for this research study. In Chapter 2, related literature is presented and research problems are classified according to the type of procurement risks faced, with research gaps identified as well. Chapter 3 proposes the mathematical models of designing optimal procurement strategies for spot market under uncertainties in the presence of one forward contract in a single period setting. The analytical results are incorporated into the reactive sourcing strategy adopted in Chapter 4's PRM framework, which provides a complete solution to the research problems raised in Chapter 1. In Chapter 5, a case study is presented to show the application of the optimal ordering decision and delivery arrangement methodologies. The summary of research,

detailed contributions of the thesis and possible future research directions are provided in Chapter 6.

Figure 1.2: The structure of the thesis

Chapter 2

Literature Review

With the research motivation of this thesis on PRM presented in Chapter 1, this chapter provides a literature overview of previous studies on this field. Related research problems are classified according to the types of uncertainties studied, followed by a summary on common risk management strategies. In Subsection 2.5, research gaps are identified and discussed.

2.1 Review methodology

In this section, a PRM structure is outlined and positioned within the supply chain risk management structure proposed by Tang (2006). Furthermore, common procurement risks are identified to set our review scope in Subsection 2.1.1. In Subsection 2.1.2, the procedure of literature search is described and the distribution of related papers is presented.

2.1.1 Procurement risk taxonomy and scope of this review

There are several definitions for procurement and risk from academics and practitioners. From the perspective of external resource management, procurement is defined as to obtain external sources for maintaining and managing a company's activities at the most favorable conditions by Weele (1994). Lysons and Farrington (2006) emphasize on the management of suppliers, so as to contribute to the competitive

advantages of the enterprise and the achievement of corporate strategy. Regarding the definition of risk and risk management, Gurnani (1984) defines risk as either the probability of not achieving a given target return or the degree of downside deviation from the expected and desired return. At the same time, risk management can be interpreted from the process perspective as risk identification, risk assessment, risk migration and risk monitoring.

To the extent of our knowledge, there is no clear definition of procurement risk management. With the aim of setting a review scope and better guiding scholars through the published articles related to PRM under uncertainty, we define PRM as follows: ***the management of procurement uncertainties to achieve competitive advantages of the enterprise, including profitability and sustainability***. The focus of PRM should consider not only the profitability but also the sustainability, which differs from previous objectives of procurement aiming only for cost reduction and profitability.

Specifically, within the volatile and dynamic market in the modern society, procurement is exposed to many kinds of uncertainties, such as changing demand, uncertain lead time and volatile price. Generally, these uncertainties and risks can be classified into two groups: operational risks and disruption risks. Based on their importance and frequency in the literature papers, we have summarized all the common procurement risks from the literature and categorized them into the two groups, as described in Table 2.1.

Table 2.1: Risks in procurement

Operational risks		Disruption risks
Uncertain supply yield ; Variable lead time		Information system disruption
Poor data reliability;	Low efficiency information system	Political unrest or warfare
Budget limitation;	Interest rate fluctuating	Extreme weather or fire
Wrong inventory record; Fluctuating exchange rate		Legal risks
Uncertain demand;	Shortage of key employees	Supplier default
Uncertain price		

Lots of risks have been studied by researchers over the years and a considerable amount of papers have been published. These papers generally deal with two kinds of procurement: physical products and service subscription. As procurement strategy is different between purchasing products and services, we focus on those common uncertainties existing in physical product purchasing, such as demand, price, lead time, yield and disruption risks. Furthermore, according to Tang (2006), supply chain risk management is divided into the following four parts: product management, supply management, demand management and information management. To further delineate the scope of our review, we inherit Tang (2006)'s supply chain risk management structure and park our PRM under supply management.

2.1.2 Supply chain risk management framework

For the purpose of a thorough review, related databases and journals are searched within the years from 1995 to 2012. Furthermore, the keywords used include price uncertainty (or risk, volatile), demand uncertainty (or risk), yield uncertainty (or risk, random), lead time uncertainty (or risk, variable), procurement risk (or uncertainty) and

disruption risks. A flow chart of literature search procedure is illustrated in Figure 2.1 to provide a clear picture of the review process and results.

Figure 2.1: Literature search flowchart

Following the searching process described in Figure 2.1, a total of 90 papers from 27 journals, such as European Journal of Operational Research, International Journal of Production Economics and Operations Research are selected. Table 2.2 is the distribution of the related papers in specific journals. A detailed description about each uncertainty and related references are provided in Subsection 2.2. In Subsection 2.3, the commonly used risk management strategies (e.g. supplier diversification and back up sourcing) are summarized.

Table 2.2: Distribution of selected papers related to procurement risk management

Journal	Number <i>N</i>	Percentage
European Journal of Operational Research	33	36.67%
International Journal of Production Economics	11	12.22%
Operations Research	9	10.00%
Production and Operations Management	4	4.44%
Management Science	3	3.33%
Omega	3	3.33%
Journal of Operations Management	2	2.22%
Naval Research Logistics	2	2.22%
IIE Transactions	2	2.22%
Computers & Operations Research	2	2.22%
Purchasing and Supply Chain Management	2	2.22%
Operations Research Letters	2	2.22%
Journal of Purchasing and Supply Management	1	1.11%
MIT Sloan Management Review	1	1.11%
Computers & Industrial Engineering	1	1.11%
Transportation Research Part E	1	1.11%
Manufacturing & Service Operations Management	1	1.11%
Others	10	11.11%
Total	90	100%

2.2 Classification of PRM under uncertainty

In order to make robust procurement decisions, buyers need to take into consideration several uncertainties. In fact, these uncertainties would not only affect the configuration of the supply base, but also the lot sizing. Therefore, it is critical to identify the possible risks in the first place. With the risks identified, suitable strategies need to be adopted to implement procurement risk management. For instance, supplier diversification is an effective solution to control the risk of uncertain supply. In the following subsections, in-depth study and developed models under different risks are discussed. Table 2.3 is the distribution of selected literature with respect to different risk categories.

2.2.1 Uncertain demand

In the modern society with highly changing circumstances, products' demands are hardly static, especially for high-tech products and those heavily influenced by fashion trends. Therefore, companies should be capable of dealing with the changing demand in order to survive and make profit. Considerable amount of research works on demand uncertainty have been done by scholars (Li and Wang, 2010; Choi and Ruszczyński, 2011; Seifert and Langenberg, 2011) in the past years. Majority of this research works study the purchasing of single product under single period setting.

For one-stage decision making, it is often the case that buyer needs to design the procurement plan such as supply base configuration, lot sizing and forward contract selection before the demand realizes (Swaminathan and Shanthikumar, 1999; Zimberg and Testuri, 2006). While the two-stage decision making process divides the single period into two stages: The first stage is similar to the one-stage model and the second stage tries

to figure out how many products need to be bought from spot market or via instance order after obtaining more accurate demand information (Burnetas and Gilbert, 2001; Erhun et al., 2008; Fu et al., 2010).

For multi-period problems, buyer's goal is to seek the optimal procurement plan for multiple periods (Martel et al., 1995; Bonser and Wu, 2001; Yan et al., 2003; Nagar and Jain, 2008). Comparing with the single period setting, more work should be done in multi-period situations as the inventory management is no longer negligible, making it impossible to directly extend the methodologies under single period to multiple periods.

Scholars have proposed several risk management approaches to handle demand risk. Firstly, it is suggested to continuously update the demand information so as to obtain a more accurate order quantity. Secondly, in order to achieve the win-win solution, it is recommended to design the production and procurement plan together, or make integrated sourcing and inventory decision. The third approach is to have a backup supply channel. After demand has realized, buyer could place an instant order or purchase from spot market to meet demand. Lastly, demand uncertainty can be mitigated using financial products such as commodity options and futures. For example, option contract is a useful tool to mitigate demand risk by giving buyers the right but not the obligation to execute the contract, at the cost of paying only a small premium upfront.

Table 2.3: Classification of research papers according to specific procurement risk

Risks		Single channel and single period	Single channel and multiple periods	Multiple channels and single period	Multiple channels and multiple periods
Operational risks	Demand	Burnetas and Gilbert (2001); Chen et al. (2006); Zimberg and Testuri (2006); Erhun et al. (2008); Mukhopadhyay and Ma (2009)	Martel et al. (1995); Burnetas and Gilbert (2001); Weng and McClurg (2003); Chen et al. (2006); Zimberg and Testuri (2006); Erhun et al. (2008), Chen and Xiao(2011); Fleischhacker and Zhao (2011)	Martel et al. (1995); Bollapragada and Morton (1999); Burnetas and Gilbert (2001); Weng and McClurg (2003); Chen et al. (2006); Zimberg and Testuri (2006); Erhun et al. (2008); Lin and Ng (2011)	Swaminathan and Shanthikumar (1999); Bonser and Wu (2001); Yan et al. (2003); Nagar and Jain (2008); Tapiero (2008); Hazra and Mahadevan (2009); Li et al. (2009); Zhang and Ma (2009); Keskin et al. (2010); Zhang and Zhang (2010); Li et al. (2011)
	Price	Siripatanakulh ajorn et al. (2006); Fotopoulos et al (2008); Arnold et al. (2009)	Chaouch (2007)	Das and Abdel-Malek (2003); Seifert et al. (2004); Spinler and Huchzermeier (2006); Woo et al. (2006); Yang et al. (2007); Fu et al. (2010);Sun et al. (2010); Xu (2010); Cheng (2011); Li and Gupta (2011); Li and Li (2011)	Li and Kouvelis (1999); Bonser and Wu (2001); Tapiero (2008); Li et al. (2009); Aouam et al. (2010); Zare et al. (2010)
	Yield	Erdem and Özekici (2002); Lin and Hou (2005); Keren(2009); Mukhopadhyay and Ma (2009)	Bollapragada and Morton (1999); Swaminathan and Shanthikumar (1999); Erdem and Özekici (2002); Grasman et al.(2007); Kelle et al. (2009); Yeo and Yuan (2011)	Agrawal and Nahmias (1997); Federgruen and Yang (2008); Burke et al. (2009); Federgruen and Yang (2009); Sun et al. (2010); Xu (2010)	Swaminathan and Shanthikumar (1999); Maddah et al. (2009); Keskin et al. (2010)
	Lead time	Hariga and Ben-Daya (1999); Hsu et al.(2009); Wang and Tomlin (2009)	Weng and McClurg (2003); Hsu et al. (2007)	Das and Abdel-Malek (2003)	Kouvelis and Li (2008); Chauhan et al. (2009)
Disruption risks			Wilson (2007)	Ruiz-Torres and Mahmoodi (2007); Wagner et al. (2009); Campbell and Jones (2011)	Yan and Liu (2009); Costantino and Pellegrino (2010); Ellis et al. (2010)

2.2.2 Uncertain price

The price of raw materials especially the electrical components is not constant in the market. And oftentimes suppliers offer periodic price discount campaigns in seasons with lower demand. To stand out among competitors, buyers have to make better procurement decision under price uncertainty, including the date and quantity of purchase. Different purchasing time usually implies different purchasing price and inventory holding length, thus resulting in different levels of costs. Das and Abdel-Malek (2003) suggest developing a flexible buyer-supplier relationship to reduce price uncertainty. Sun et al. (2010) propose a two-stage fuzzy programming to model uncertain spot market price. Efforts to reduce price risk can be also found in Seifert et al. (2004), Spinler and Huchzermeier (2006) and Woo et al. (2006).

In order to handle price risk, three most commonly used strategies are as follows. Firstly, different procurement time and quantity would affect the inventory holding cost and inventory level, so one way to reduce price risk is to integrate sourcing and inventory decision. Furthermore, flexible contract is also a useful method to mitigate price risk. An inflexible contract requires the buyer to determine not only the quantity but also the exact delivery date, while flexible contract usually gives buyer the freedom to collect items within a period. Last but not least, with the continuous development of financial market, many commodities can be bought in the form of option contract or futures contract. These financial tools can also help buyers to hedge price risk by locking in a fixed price a few months or quarters before delivery, regardless of the spot price on the delivery day.

2.2.3 Uncertain yield

Uncertain supply yield can come from a number of sources. For instance, because of the supplier's limited production capability, it could not deliver all the products on time (Erdem and Özekici, 2002; Yang et al., 2007; Keren, 2009). Another situation is that not all the supplier's products meet the quality requirement, so only a fraction of products can be used for production (Agrawal and Nahmias, 1997; Bollapragada and Morton, 1999; Maddah et al., 2009). All these reasons could cause the buyer not able to receive enough products to meet the actual demand. Maddah et al. (2009) study a problem which has two types of supplies. One is type A which is of perfect quality but higher cost, while type B is the one with imperfect quality but lower cost. The classic single period (newsvendor) and economic order quantity (EOQ) models are extended by incorporating random supply and yield uncertainty. The proposed model proves that accounting type B product to supplement the supply from type A would significantly increase profits comparing with only sourcing from type A. For more detail of yield uncertainty, readers can refer to Yano and Lee (1995) which is a comprehensive and excellent literature review of lot sizing under uncertainty.

Facing uncertain yield, two approaches are most widely used. Firstly, supplier diversification uses multiple suppliers when the available suppliers are not reliable. This could help to reduce the yield uncertainty. Collaboration with supplier is another mechanism to minimize uncertain yield. Capital investment to improve production line or inspection center is an instance (Talluri et al., 2010).

2.2.4 Uncertain lead time

When buyer asks for quotation, supplier usually replies with price and lead time. If the uncertainty of lead time can't be controlled properly, it would increase total cost and reduce customer service level. Conducting proper ways to control the uncertainty of lead time is important and necessary. Some of the following approaches are commonly used by buyers, such as deciding the optimal ordering time and using back up supply channel.

In fact, the variable lead time requires buyer to optimize and obtain the optimal ordering time decision. Hariga and Ben-Daya (1999) take the variable lead time and the partial lead time distributions into consideration, so as to determine the optimal reduction in procurement lead time distribution and optimal ordering policy. Hsu et al. (2007) also examine the effects of lead time uncertainty on the ordering policy. Besides, product expiration date and capital limitation are also considered. The results show that the retailer's profit is highly influenced by the uncertain lead time and there should be compensation mechanism to induce supplier collaboration.

There is another situation where component costs are too high to be kept as inventory. So, many firms optimize the best ordering time with the distribution of lead time, expected holding and backlogging cost. Chauhan et al. (2009) investigate such a model and propose an algorithm to solve it. Moreover, many firms begin to place orders overseas. This would bring low purchasing unit cost but would also increase lead time risk. However, from another perspective, a more accurate demand forecasting would help buyer to manage the lead time uncertainty. Wang and Tomlin (2009) show that a firm becomes less sensitive to the lead time uncertainty when the demand forecast updating process becomes more efficient.

2.2.5 Disruption risks

In the face of supplier disruption risk, buyer may configure the supply base with back up suppliers. But, using more suppliers usually results in more operational cost. So, it is important to find the optimal number of suppliers. Ruiz-Torres and Mahmoodi (2007) use decision tree to determine the number of suppliers needed. In fact, the model investigates two situations: The failure probability of each supplier is equal or the failure probability of each supplier is unequal. The results show that when the reliability of supplier is really high, sole supply strategy may be optimal. But as the supplier becomes less reliable, additional suppliers may be needed to obtain the lowest cost.

As for supplier failure, most of the models assume that the failure probability of suppliers is independent. Actually this may not be right in all situations; Wagner et al. (2009) use copula functions to capture the default dependence between suppliers. Copula function is a way to represent joint distribution. An empirical data from automotive suppliers helps to illustrate the importance to investigate supplier default dependence in a supplier portfolio. Costantino and Pellegrino (2010) want to choose between single sourcing and multiple sourcing when there is supplier default risk. A Monte Carlo simulation model is analyzed and the advantages of choosing multiple sourcing in risky environments are examined.

2.3 PRM strategies under uncertainty

Based on the analysis of different types of risks in procurement in Subsection 2.2, we have identified that the following risk management strategies (summarized in Figure 2.2) are effectively and widely used when studying procurement risk management: supplier

diversification, back up sourcing, flexible contract design, supplier development program and integrated procurement and inventory decision making. For instance, supplier diversification and financial products (option or futures contracts) are widely adopted for mitigating demand risk, and back up sourcing is utilized to address lead time volatility. Similarly, specific methods are used to mitigate the lead time and disruption risks. A review of the above common strategies to deal with these uncertainties is provided from Subsection 2.3.1 to 2.3.4.

Figure 2.2: PRM strategy

2.3.1 Supplier diversification

Supplier diversification is one of the methods to mitigate risk and researchers have formulated models with objective mainly for minimizing the cost. Table 2.4 summarizes the findings in supplier diversification.

Facing uncertain yield, demand and price, buyers try to diversify their supply base in order to prepare for the risks. Small orders from a large number of suppliers can reduce yield uncertainty. On the other hand, the fixed cost with each supplier would increase the total cost. So, diversification approach doesn't mean having as many suppliers as possible. Agrawal and Nahmias (1997) examine how many suppliers are needed to be selected when the yield of each supplier's products is different. The result shows that the optimal expected profit is concave in the number of suppliers N . The concavity means the optimal solution exists. Under the assumption of no fixed cost, it is proved that the optimal profit is concavely increasing with the number of suppliers N because the variance of yield decreases with N . However, if there is a fixed cost, the optimal number of supplier N is chosen to make the tradeoff between fixed costs and the benefit of diversifying. Swaminathan and Shanthikumar (1999) study supplier diversification under demand uncertainty using both single period and multi-period settings. Moreover, two types of suppliers are considered: one with high cost and high reliability, while the other with low price but low reliability; expected cost are expressed with parameters of cost and demand. Fu et al. (2010) decide the sourcing quantity to be executed from the option contract; they firstly select a supply base which has the following characteristic: no option contract can dominate the other one in term of the reservation cost and holding costs. Otherwise, this kind of option contract will not be selected in the market. A new concept of measuring the effects of supplier portfolio is proposed by Fu et al. (2010):

$$PE = \frac{C_s^* - C_m^*}{C_m^*},$$

where PE is used to show the relative error of an optimal single contract cost (C_s^*) compared to the optimal portfolio procurement cost (C_m^*). In addition, a two-period

model is also examined and optimal properties are discovered to show the effect of inventory. Their study also shows that correlation between demand and spot price can greatly affect the order decisions. In a high demand-spot price correlation environment, option contract play a more important role in serving the demand. Unlike the previous papers which consider only cost, Zhang (2010) takes the total purchase quantity attribute and service level attribute into account when designing the optimal procurement mechanism. He also points out that the optimal procurement plan consists of a list of nonlinear contracts with different quantity and service levels. To further simplify the results, the value of the two attributes are checked and found to have different implications. Thus, a fixed level which consists of a target service level and price-quantity menu is proved to help buyer yield optimal profit. Zhang and Zhang (2010) try to purchase products from a group of suppliers which quote different prices and order restrictions (minimum and maximum order sizes). Purchasing and holding costs are also considered. This problem is modeled as a mixed integer programming and solved with branch and bound algorithm. Besides, Hazra and Mahadevan (2009) use multiple suppliers. But the difference of Hazra and Mahadevan (2009) and Zhang and Zhang (2010) is that Harzra and Mahadevan (2009) adopt the equal allocation strategy among the suppliers. Closed form analytical solutions are provided and the results provide the following managerial insight: It is better to have a pre-qualified supply base with greater capacity heterogeneity rather than simply increase the number of suppliers.

Table 2.4: An overview of PRM models with supplier diversification strategy

Reference	Demand	Price	Yield	Lead Time	Disruption	Correlation	Objective
Agrawal and Nahmias (1997)	Fixed	Fixed	Random	×	×	×	Minimal expected cost
Swaminathan and Shanthikumar (1999)	Discrete	Fixed	Fixed	×	×	×	Minimal total cost under single and multiple periods
Federgruen and Yang (2008)	Random	Fixed	Random	×	×	×	Minimal cost with service constraint
Federgruen and Yang (2009)	Random	Fixed	Random	×	×	×	Minimal total cost and service constraint
Hazra and Mahadevan (2009)	Random	Random	×	×	×	×	Minimal total cost
Fu et al. (2010)	Random	Fixed	Random	×	×	Demand and price	Minimal total cost for single and two periods
Xu (2010)	Random	Random	Random	×	×	Yield and instant price	Maximal profit for buyer and manufacturer
Zhang (2010)	Random	Random	×	×	×	Price and demand	Maximal expected profit
Zhang and Zhang (2010)	Random	Fixed	×	×	×	×	Minimal total cost
Federgruen and Yang (2011)	Random	Random	Random	×	×	×	Minimal cost under multiple periods

To examine the effects of supplier diversification under uncertain supply, Federgruen and Yang have done a lot of contributions on supply management with yield uncertainty taken into consideration. Federgruen and Yang (2008) select which of the given set of suppliers to retain and how much to order from each. The objective is minimizing the total procurement cost and meeting the uncertain demand with a given probability. Two kinds of situations are considered. Firstly, all the N potential suppliers have the same fixed cost

and yield distribution. Secondly, under the general case where suppliers have different fixed costs and yield factor distributions. Large-deviations technique and the central limit theorem based approximations are used to obtain the optimal solution. Federgruen and Yang (2009) make further contribution of supplier diversification by differentiating the service constraint model, where the delivered and usable units must cover the demand at a certain probability and the total cost model, where the orders are determined so as to minimize the total cost. One of the most important contributions of this paper is to prove the difference of service constraint model and total cost model under multiple suppliers with unreliable yields. These two models are known to be the same with single and fully reliable supplier. To further analyze the utilization of supplier diversification strategy, Federgruen and Yang (2011) develop a model to find the optimal procurement decision under multiple periods. An important contribution of this paper is to propose a two-part fee structure paid to supplier i in period t , c_{it} :

$$c_{it} = c_{it}^o + c_{it}^e p_{it}, \quad i = 1, \dots, N, \quad t = 1, \dots, T,$$

where c_{it}^o is the price charged by supplier i in period t for every ordered unit and c_{it}^e is the additional price charged by supplier i in period t for every effective unit delivered. They develop an efficient algorithm and identify the optimal procurement strategy. For example, it is no longer optimal to use a base-stock policy in contrast to the classical model. Instead, the paper suggests retaining k^* suppliers that are cheapest in terms of the effective cost rates. The value of k^* depends on the following factors: suppliers' yield characteristics, demand distribution and cost parameters.

Under the recent research of financial products' applications in supply chain, another emerging direction of using supplier diversification is for mitigating uncertain price. Buyers may choose to buy some financial products to control risks, such as option

contracts, futures and other derivatives. Woo et al. (2006) use the case of a local distribution company to explain how to determine the extent to which it should rely on spot markets, forward contracts and long term tolling agreement. The result shows that efficient frontier is a useful decision making tool. Moreover, Aouam et al. (2010) use both financial (option and futures contracts) and non-financial contracts (long term contract) as gas procurement source. The naïve strategy is to hedge a fixed fraction of winter demand and equally allocate among available procurement sources. An alternative dynamic strategy models the problem as a mean-risk stochastic problem which is proved to be better by comparing with the naïve strategy. Rocha and Kuhn (2012) use the mean-variance optimization model for the management of electricity procurement from spot market and other financial derivatives. By aggregating periods into macro periods and restricting the decision rules to those that are affine in the history of the risk factors, the complex multiple stage model is converted into a tractable quadratic program. The numerical experiments highlight the superiority of the method in enabling scalability to multiple stage models.

2.3.2 Back up sourcing

Back up sourcing is a commonly used strategy to meet customer's uncertain demand. As demand information is not accurate until the selling season approaches, it is quite common for buyers to have back up sourcing with demand information updating. Table 2.5 shows the overview of PRM model with back up sourcing strategy.

Burnetas and Gilbert (2001) make a tradeoff between more accurate demand information and the increasing price as selling season approaches. After modeling the uncertain demand using Bernoulli process and deriving the optimal solution, a numerical

study is provided to give management insights. Similarly, the benefit of information updating is also examined by Yan et al (2003) and it is modeled in a dual supply mode. There exists two suppliers with unit cost c_i and lead time L_i , $i = 1, 2$, where $c_1 < c_2$ and $L_2 < L_1$. This means the convenience of using a supplier with short lead time always goes along with paying for a high unit price. An initial order can be placed to the cheap but slow one, and reactive supply can be ordered from the fast and expensive one to meet demand. The obtained analytical optimal order solutions are validated and tested for purchasing micro-controller in an industry company.

Table 2.5: An overview of PRM models with back up sourcing strategy

Reference	Demand	Price	Yield	Lead Time	Disruption	Correlation	Objective
Burnetas and Gilbert (2001)	Random	Random	×	×	×	×	Maximize expected profit
Yan et al. (2003)	Random	Fixed	×	Fixed	×	×	Minimize total cost
Kouvelis and Li (2008)	Fixed	Fixed	Random	Random	×	×	Minimize cost
Fu et al. (2010)	Random	Random	×	×	×	Demand and price	Minimize cost
Sting and Huchzermeier (2010)	Random	×	×	×	×	Supply and demand	Maximize profit
Xu et al. (2010)	Random	Random	Random	Random	×	×	Minimize cost

Another most commonly studied problem is to try to determine the optimal procurement quantity at the beginning of the ordering stage and the amount to order from back up sourcing channel during the selling season. To have a quick response to the urgent demand, back up sourcing supplier tends to offer a very short lead time to buyers.

At the same time, the price of products from back up supplier is higher compared with other suppliers who have a relatively longer lead time. Sting and Huchzermeier (2010) study a case with one overseas supplier and one back up supplier. The shortages of overseas supplier are the lack of reliability and flexibility. A back up supplier can help to improve the responsiveness. Xu et al. (2010) have a totally different assumption of whether overseas supplier is reliable or not. They consider to source from two urgent supply options besides the long lead time overseas supplier. The overseas supplier is prime and the product's quality is good, whereas the urgent supplier's products are inferior in quality and expensive. The contribution of their paper is to adopt Stackelberg game model to evaluate the involvement of two urgent back up supply: the common price-only contract, and a contract menu consisting of a transfer payment and a lead time quotation (L, T) . Furthermore, with sensitivity analysis, it is found that (L, T) contract has higher advantages over the common price-only contract when the market acceptance of substitutable modules and the uncertain nature of urgent supplier are high. Some prime suppliers can also offer instance orders. So instead of finding multiple back up sourcing channels, some of the buyers obtain the benefits from the same prime supplier. Li et al. (2011) consider how to place both initial order and supplementary order in a multi-period situation. The uniqueness of Nash equilibrium is proved and closed-form Nash equilibrium solution is found out when parameters are stationary. And the numerical study shows the back up order option is beneficial for the following scenarios: lower cost, lower value, lower inventory cost of supplier, higher inventory cost of buyer and higher demand variation.

With the research of financial markets, a lot of industry professionals and researchers try to protect company from risks by tapping commodity trading platform, such as spot market. Seifert et al. (2004) study the usage of spot market to meet customer's uncertain demand. Chen and Liu (2007) quantify the benefits of using a spot market from both a buyer's and a supplier's perspectives. The optimal order quantity is obtained under uniformly distributed demand and spot prices. Apart from spot markets, the application of option contracts in procurement is also adopted by researchers (Spinler et al., 2003, Spinler and Huchzermeier, 2006). An option contract gives a buyer the right, but not the obligation to purchase at an exercise price from a seller within a pre-specified time period. In order to gain the option right, the buyer has to pay an option fee. If the buyer does not want to execute the contract, the option fee will not be refunded. This kind of design ensures buyers' flexibility to respond according to actual demand. Meanwhile, it provides certain compensation for suppliers in the form of option fees. Fu et al. (2010) derive the optimal number of option contracts and the corresponding lot sizes from them and a spot market.

The adoption of back up supplier is also a useful method to deal with lead time uncertainty. Kouvelis and Li (2008) examine when and how many to order from a back up supplier to minimize the total cost. The benefits of using flexible back up supplier in the form of dual sourcing are investigated using numerical analysis.

2.3.3 Flexible contract design

Flexible contract designing is another approach being used substantially when facing procurement uncertainty. Risk and cost can be reduced by a flexible cooperation

mechanism between buyer and supplier, such as a flexible sourcing contract. Table 2.6 shows an overview of PRM model with flexible contract design.

Signing a flexible contract with supplier can also be used to reduce price risk. Li and Kouvelis (1999) try to figure out the optimal purchasing time and quantity of “time-inflexible contract” and “time-flexible contract” respectively. Time-inflexible contract requires buyer to determine not only the exact order quantity but also the purchasing time, while time-flexible contract allows buyer to purchase the specified quantity over a given period of time. Inderfurth and Kelle (2011) study a case where both a capacity reservation contract and a spot market are used to meet uncertain demand. The capacity reservation contract gives a buyer the right not to exercise the reserved quantity with a pre-paid reservation fee. It is proved that the combined sourcing solution is superior over a single procurement channel in certain market conditions. In addition, risk sharing mechanism is also incorporated. The optimal result is obtained by calculating the net present value of the sum of purchasing cost and inventory cost. Similar time flexible contract is also used by other researchers to mitigate procurement risk (Fotopoulos et al., 2008; Xiong et al., 2011; Buzacott and Peng, 2012). Option contract is another form of flexible contract. If the spot market price is lower than the strike price specified in the option contract, buyer can choose not to execute option contract (Spinler and Huchzermeier, 2006; Fu et al., 2010).

Another effective way is the utilization of risk sharing contract. Chen et al. (2006) develop a two stage decision model. The manufacturer determines the production quantity in the first stage when there is little information about the actual demand. In the second stage, as the selling season approaches, the buyer would place the order. At last, a risk

sharing contract is proposed to maximize the overall profit and each partner's interest is also ensured. In addition, the procurement decision would also affect the inventory holding cost, integrated sourcing and inventory decision which is also found in literature. In addition, one innovative approach of promoting cooperation between buyer and retailer is to use option contract. Tapiero (2008) incorporates options contract to optimize the risk premium so as to set up the optimal-order policy. Zhao (2010) suggests using the negotiating of option contract price and the exercise price instead of wholesale price mechanism to facilitate the production and procurement in the supply chain. To obtain the system-wide optimal expected profit for the supply chain, they take the whole supply chain as a centralized entity. The result is compared with the wholesale price mechanism in manufacturer-retailer cooperation. It is demonstrated that any option contract in the corn can bring in Pareto improvement.

Table 2.6: An overview of PRM models with flexible contract design

Reference	Demand	Price	Yield	Lead Time	Disruption	Correlation	Objective
Fu et al. (2010)	Random	Random	×	×	×	×	Minimize total cost
Zhao et al. (2010)	Random	Random	×	×	×	×	Maximize profit

2.3.4 Other strategies

Apart from supplier diversification and back up sourcing strategies, there are other commonly used strategies, such as supplier development program and integrated procurement-inventory decision making. In addition, the prediction market is an effective

approach to management demand uncertainty (Guo et al., 2006). There are described in Subsection 2.3.4.1, 2.3.4.2 and 2.3.4.3, respectively.

2.3.4.1 Supplier development program

Actually the yield uncertainty can be reduced through supplier development program, for instance, capital investment to improve the production line or quality inspection center. Therefore, the question is how much resource should be invested. Lin and Hou (2005) develop a model to reduce the yield variability through proper capital investment and to search the optimal ordering policy. Numerical studies find that the capital investment brings about an average savings of 13.6%. Talluri et al. (2010) also advocate that manufacturing firms should allocate resources to improve suppliers' capabilities and performance, including quality management, product management and cost reduction. The creativity of this paper is to use Markowitz's model to assist buyer and manufacturing firms in optimally allocating supplier development dollars among multiple suppliers. The other contribution is to present an analytical approach to addresses the issue of risk in the capital investment in developing suppliers.

2.3.4.2 Integrated procurement and inventory decision making

Integrated sourcing and inventory decision making is commonly used. It is often the case that suppliers offer low price when they want to promote sales or clear excess inventory. And the low price lasts for a certain period before it returns to the normal price level. Chaouch (2007) considers such a problem and tries to design the optimal replenishment plan by using stochastic model. The optimal strategy is to replenish when the inventory falls below a certain level. Inventory management is seen as a risky investment for future by Tapiero (2008). By using exponential utility function and

modeling in a two period problem setting, it proves that zero-inventory can be replicated by option contract with the optimal order quantity. Facing uncertain raw material price, Arnold et al. (2009) take the uncertain holding cost and uncertain demand into consideration by adopting a deterministic optimal control approach to design the procurement plan. The optimal policy turns out to be involving impulse and just in time procurement.

2.3.4.3 Prediction market approach

In addition, the prediction market approach is proved to be quite effective in supply chain risk management by providing an accurate demand forecast and promoting channel coordination. The market approach rewards participants for improving the market prediction. Guo et al. (2006) design a real money futures market and a retail index with a payoff dependent on the future realization of the macro factor. By the adoption of this prediction market approach, useful information is absorbed and market participants are motivated to produce a reliable forecast. Therefore, the incorporation of prediction market approach into supply chain management helps to achieve accurate demand forecast sharing, reduce the order variance and improve the expected supply chain profit. With the popularity of social network (e.g. Twitter), the simulation result of a Twitter-based prediction market shows the price dispersion is small as agents acquire more information in the network. Network based prediction market has a better prediction and the finding gives insight about how social network affects information acquired by agents so as to affect the overall market performance (Qiu et al., 2011). The similarity between the spot market trading approach and the prediction market approach is that both of them can be used for managing demand uncertainty. The difference is that the spot market trading

approach tries to minimize risk impacts after risk events happen, while the prediction market approach can help to reduce the uncertainty of risk factor before risk events happen.

2.4 PRM under dependent risks in the presence of spot market

In Subsection 2.2, we have classified PRM literature papers according to the specific risks studied. Common PRM strategies are then summarized in Subsection 2.3. Based on our discussion of industry challenges in Chapter 1, we find that there is a pressing need to address PRM problems under dependent demand, price and yield risks. In order to address these research problems, multiple strategies can be combined to leverage on their respective strengths. For instance, companies can enjoy the combinatorial benefits if they utilize both proactive supply (forward contract) and reactive sourcing (spot market). In this subsection, key research papers related to our research problem and their results are discussed.

2.4.1 Proactive and reactive purchasing planning under dependent demand, price and yield risks

The PRM literature relevant to the above topic mainly comes from two streams: the literature on order allocation under random yields and the literature on procurement decision making in the presence of reactive supply. In the first stream, Yano and Lee (1995) provide a comprehensive literature review for determining lot sizes when production or procurement yields are random. The modeling of costs and yields is

summarized and quantitative approaches are presented. Several papers study the decision making for backup sourcing. Gurnani et al. (2000) develop a model to help make both procurement and production decisions for an assembly system facing unstable demand. The number of suppliers is two and they are both unreliable. When supply is subject to yield losses and cost functions are linear, Chen et al. (2001) prove that having an additional backup supplier is more suitable comparing with single sourcing. Two types of suppliers are usually considered. One type is totally reliable, while the other is exposed to disruption risks. Maddah et al. (2009) study a procurement order allocation problem with two types of suppliers. One type has perfect quality but higher costs, while the other type has imperfect quality and lower costs. The classical single period newsvendor and economic order quantity models are extended by incorporating random supply and yields. The traditional procurement literature on order allocation under yield risks provides useful modeling and planning methods for assisting decision making. However, the effectiveness of reactive supply is largely overlooked.

Within the second stream, the research work of Seifert et al. (2004) is close to our research work. Seifert et al. (2004) quantify the benefits of using a spot market from a buyer's perspective. In their model, they have considered the demand and spot price volatilities, the correlation between demand and spot prices and the risk averse attitude of the buyer. The demand and spot price are modeled as bivariate normal distribution in this model, and the proposed objective function for BS is to maximize the mean-variance objective function $Z(Q)$:

$$Z(Q) = E(q) - kVar(q), \text{ where } k > 0.$$

After deriving the equation of expected profit $E(q)$ and profit variance $Var(q)$, buyer links them to form a comprehensive evaluation measure by the risk aversion parameter k of the buyer. The analytical form of procurement quantity from contract supplier is discovered thereafter. The result tells us that the optimal order quantity is positively related to the mean of demand and spot price, but negatively related to the risk aversion parameter and the demand standard deviation. This means that back up sourcing is more important when market is not stable and buyer is much more risk averse. They analyze and compare four procurement scenarios: pure contract sourcing, contract sourcing with buying-only spot market, contract sourcing with selling-only spot market and spot market buying and selling (BS).

Based on the review of literature papers in the above stream, we find that there is no PRM study about using spot market as a reactive sourcing channel when facing yield risk. An even more challenging work is to study this problem under dependent demand, price and yield risks. Research gaps related to this topic are summarized in Subsection 2.5.

2.4.2 An integrated PRM framework in the presence of spot market

When dealing with yield risk, the utilization of a pool of suppliers (forward contract suppliers) to diversify risks is also quite common and effective in the industry (Agrawal and Nahmias, 1997).

In the area of utilizing multiple suppliers under yield uncertainty, Agrawal and Nahmias (1997) derive the optimal number of suppliers and the corresponding lot sizes. They have studied the following two cases: identical suppliers and non-identical suppliers. They discover that the expected profit is strictly concave in the order quantity and the number of suppliers. Another observation is that the ratio of optimal order size is

inversely proportional to the yield variance. If suppliers want to increase their shares of the total order, they have to improve their yield performances. Federgruen and Yang (2008) propose a model to configure the supply base in the presence of yield and demand uncertainties under a single period setting. The generated optimal procurement plan includes the optimal set of suppliers to be chosen and the optimal orders to be assigned to each supplier. If there is no reactive supply after the uncertain demand or yield is realized, the unmet demand is usually penalized at a certain value and the extra products are also salvaged.

As the shortcomings from contract suppliers can be made up and compensated by the reactive supply (using spot market), therefore, to deal with the procurement risk management, it is essential to utilize both supply sources and take related risk factors into consideration, such as demand, price and yields risks. At the beginning of every procurement period, the buyer will place orders on the supplier pool of contract suppliers. Spot market with negligible lead time is adopted as the reactive supply source to meet unexpected demand or sell extra stock.

Apart from optimal ordering decision making, the accuracy of lead time and timely delivery is a prerequisite of efficient manufacturing and sales work. It is often the case that buyers select those suppliers with the lowest cost but do not pay much attention to the lead time uncertainty. When the delivery cannot meet the deadline, suppliers could not deliver all the products or even a portion of them. This shortage would cause manufacturing disruption, resulting in revenue loss. It is necessary to consider lead time uncertainty when selecting suppliers and making order allocation decisions.

In order to address our research problem, we need to study proactive sourcing with multiple forward contract suppliers in the presence of spot market when facing dependent risks. In addition, delivery arrangement decision making should also be optimized in order to reduce delivery cost and lead time.

2.5 Research gaps

According to our review, literature papers have extensively studied the feasibility of spot markets to manage demand uncertainties, but limited attention is on the possibility of adopting reactive supply to manage yield uncertainty. Moreover, no literature has investigated procurement decision making under environments with interdependent demand, yield and spot price uncertainties. In Chapter 3, we have proposed a model to fill this research gap. More specifically, we have generalized and expanded Seifert et al. (2004)'s research work by considering yield risk and interdependencies among demand, price and yield risks.

As discussed in Subsection 2.4.2, yield risk can also be diversified within a supplier pool. To make the proposed solutions more generic, a novel PRM framework is constructed in Chapter 4 which expands the model proposed in Chapter 3 by incorporating multiple forward contract suppliers. This would assist decision making in optimal ordering among multiple forward contract suppliers and the spot market, as well as delivery arrangement.

2.6 Summary

Procurement decision making under uncertainties has attracted considerable attention from researchers and practitioners from different echelons of supply chain such as manufacturers, wholesalers, distributors and retailers. Although researchers have suggested various operations research techniques to mitigate the procurement uncertainties, no detailed and thorough review work exists on procurement risks as of now, let alone on procurement risk management, which not only needs to address the risks of price and lead time, but also requires sophisticated techniques for supply and demand uncertainties analysis.

This chapter firstly gives a comprehensive overview of procurement uncertainties including the taxonomy of procurement risks, such as demand, price, yield, lead time, and disruption risks with detailed descriptions, and applicable approaches are discussed for analyzing different uncertain scenarios.

Following that is the discussion on the implications of current research findings. A list of classic strategies and latest progresses are categorized and summarized after reviewing the published papers in the procurement risk domain.

In Subsection 2.5, research gaps are identified between the real-world needs and the current research outcomes.

Chapter 3

Proactive and Reactive Purchasing Planning under Dependent Demand, Price and Yield Risks

In this chapter, procurement utilizes the combinatorial benefits of proactive supply (a contract supplier) and reactive supply (a spot market). The uncertainties of yields, spot prices and demand, and the correlations among them are also taken into consideration when designing procurement plans. The objectives of this research are to evaluate the effectiveness of dealing with uncertain supply using the spot market along with the contract supplier and to model the dependences among all the potential uncertainties. This research also seeks high expected profits without overlooking the associated variances. The analytical expression to determine the optimal order quantity is obtained under the most general situations where commodities can be both bought and sold via the spot market. Some properties are derived to provide useful managerial insights. In addition, reference scenarios, such as pure contract sourcing and the spot market restricted for buying or selling only, are included for comparison purposes.

3.1 Problem background

In this chapter, a procurement model where a buyer can serve customer demand via both a contract supplier and a spot market is studied. The contract price is much lower than the average spot price, but the contract supplier requires a relatively longer lead time. Because of uncertain demand and random yields, the buyer has to turn to the spot market to satisfy unmet demand or sell additional products to the spot market. The most general scenario where the spot market is used for BS is analyzed and the analytical expression of the optimal order quantity from the contract supplier is obtained. The risk attitude of a buyer affects the ordering decision greatly; a more risk-averse buyer prefers a reliable reward while the opposite seeks a possible higher profit even if the associated profit variation is also larger. The correlations among uncertainties are also incorporated. The effects of risk aversion, uncertainties and their correlations on the optimal procurement decisions are investigated. To illustrate the spot market's effectiveness in managing demand and yield risks, three other scenarios are provided for comparison: pure contract, the spot market restricted for buying only and the spot market restricted for selling only.

The organization of this Chapter is as follows: In Section 3.1, the related background and literatures are reviewed. In Section 3.2, a BS model is described in detail and the other three scenarios (PC, BO and SO) are presented. In Section 3.3, a detailed computational study is provided. Conclusions and future research directions are stated in Section 3.4. All derivations and proofs are included in appendices.

3.2 Problem formulation and solution approach

Tang (2006) classifies supply chain risk management into four parts: product management, supply management, demand management, and information management. PRM is a part of supply management and mainly focuses on assisting procurement decision making under uncertainties. The aim of PRM is to manage uncertainties in procurement to achieve competitive advantages of enterprises, including both profitability and sustainability.

Based on the gap as discussed in Subsection 2.5, this research combines both PPRM and RPAM strategies to achieve profitability and sustainability. Furthermore, the effects of the buyer's risk aversion, the uncertainties of demand, yields and spot prices, and the correlations among them on the optimal procurement decisions are illustrated.

A risk-averse buyer is exposed to uncertain demand, yields and spot prices. The objective of this research is to maximize the risk-averse buyer's profit while minimizing the associated variation at the same time. The usage of reactive supply is explored. A BS model is firstly studied in Subsection 3.2.1 and three other strategies are investigated in Subsection 3.2.2. The buyer is responsible for purchasing components and selling them to customers with random demand. There are two supply options: Under option one, the buyer selects a contract supplier which offers a fixed and low price. This supplier has random yields. Under option two, the buyer procures from a spot market with an essentially negligible lead time but stochastic spot prices. Demand, yields and spot prices are all correlated. In addition, the buyer is risk-averse with a risk aversion parameter. Here is the summary of parameters:

y : Yields are a normal random variable with mean μ_y and standard deviation σ_y ;

s : Spot prices are a normal random variable with mean μ_s and standard deviation σ_s ;

d : Demand is a normal random variable with mean μ_d and standard deviation σ_d ;

Q : Order quantity from the contract supplier;

Y : Quantity delivered from the supplier with mean μ_Y and standard deviation σ_Y ;

$\rho_{d,s}$: Correlation coefficient between demand and spot prices;

$\rho_{y,s}$: Correlation coefficient between yields and spot prices;

$\rho_{d,y}$: Correlation coefficient between demand and yields;

r : Sales price per unit;

w : Wholesale price per unit paid to the contract supplier;

p : Unit penalty cost of unmet demand;

g : Unit salvage value of excess inventory;

Π_{BS} : Buyer's profit under BS;

$\Pi_{PC}(Q)$: Buyer's profit under PC;

$\Pi_{BO}(Q)$: Buyer's profit under BO;

$\Pi_{SO}(Q)$: Buyer's profit under SO;

$E(\Pi_{BS})$: Buyer's expected profit under BS;

$Var(\Pi_{BS})$: Buyer's profit variance under BS and

k : Buyer's risk aversion parameter.

3.2.1 BS model

In this subsection, the spot market is used for both BS. By obtaining the analytical forms of the buyer's expected profit and profit variance, the corresponding optimal order quantity from the contract supplier is derived. Uncertain demand, yields and prices, and

the correlations among them are all taken into consideration when deriving the closed-form result of the optimal order quantity.

The buyer orders Q units with a unit price w from the contract supplier at time 0. It is possible that the delivered quantity Y is not enough to meet demand d . If this is the case, the buyer will buy $(d - Y)^+$ units with a spot price s at time T . The expected spot price is usually larger than or equal to the price w . Products from both channels are sold to customers with a unit sales price r . The other possibility is that the delivered quantity Y is larger than or equal to demand d . After selling d units to customers with the price r , the buyer sells the remaining $(Y - d)^+$ units via the spot market with the price s . In both situations, the purchasing costs from the contract supplier are wY rather than wQ , as the buyer only pays for the delivered and qualified products.

Among the literature of supply chain modeling, normal distributions are commonly used to model uncertain demand (Martel et al., 1995, Hazra and Mahadevan, 2009) and random yields (Agrawal and Nahmias, 1997, Federgruen and Yang, 2009). For the distribution of spot prices, Seifert et al. (2004) illustrate that it can be efficiently estimated using a normal distribution. The correlations among demand, price and yield uncertainties are also considered. If demand is high, investors and speculation parties usually anticipate price increases in spot markets. Therefore, the correlation coefficient $\rho_{d,s}$ between demand and spot prices is positive. This positive correlation coefficient is also found in Seifert et al. (2004). Regarding the correlation between demand and yields, Federgruen and Yang (2011) point out that demand and yields are correlated because of common dependent factors. Also, according to the statement of Nagali et al. (2008), “in periods of high demand, hi-tech suppliers place original equipment manufacturers (OEMs) such as

HP under allocation whereby they supply only a fraction of the OEM's total demand." Thus, demand and yields are negatively correlated. Under volatile environments, suppliers are more unreliable. This will result in higher spot prices. So, the correlation coefficient $\rho_{y,s}$ between yields and spot prices may also be negative.

The buyer is risk-averse and expects to obtain stable profits. Therefore, the buyer makes a trade-off between high expected profits and high profit variances. The objective is to maximize $Z(Q) = E(\Pi_{BS}) - kVar(\Pi_{BS})$ with $k > 0$, where Π_{BS} is the buyer's profit. This kind of objective function is widely recognized in portfolio theory and yields mean-variance efficient outcomes (Markowitz, 1952, Seifert et al., 2004). The profit Π_{BS} is the difference between sales revenues and purchasing costs. The result can be written as follows:

$$\begin{aligned}\Pi_{BS} &= rd + s(Y - d) - wY \\ &= rd + s(yQ - d) - wyQ.\end{aligned}$$

In order to obtain the optimal order quantity, the expected profit $E(\Pi_{BS})$ and the profit variance $Var(\Pi_{BS})$ should be computed. The derivation of the expected profit $E(\Pi_{BS})$ is shown in Appendix 1 and the result is as follows:

$$E(\Pi_{BS}) = (r - \mu_s)\mu_d - \rho_{d,s}\sigma_d\sigma_s + [(\mu_s - w)\mu_y + \rho_{y,s}\sigma_y\sigma_s]Q. \quad (1)$$

We observe that the expected profit $E(\Pi_{BS})$ increases when the order quantity Q increases, if the yield coefficient of variation (COV) $\frac{\sigma_y}{\mu_y}$ is smaller than $\frac{w - \mu_s}{\rho_{y,s}\sigma_s}$. If the yield COV $\frac{\sigma_y}{\mu_y}$ is larger than $\frac{w - \mu_s}{\rho_{y,s}\sigma_s}$, the expected profit $E(\Pi_{BS})$ decreases with the increase of the order quantity Q . Thus, the buyer's incremental transaction with the supplier is not profitable if the yield COV is larger than $\frac{w - \mu_s}{\rho_{y,s}\sigma_s}$. But, if the yield COV is reduced by either

increasing the yield mean or decreasing the yield standard deviation, the purchasing of additional items is profitable and the buyer can order as many products as possible to obtain larger expected profits. However, the additional items purchased may increase profit variations. Therefore, the profit variance $Var(\Pi_{BS})$ needs to be computed.

Based on the definition of variance, we have that

$$\begin{aligned} Var(\Pi_{BS}) &= E[(\Pi_{BS})^2] - [E(\Pi_{BS})]^2 \\ &= E[(r - s)^2 d^2] + 2E[dY(r - s)(s - w)] + E[(s - w)^2 Y^2] - [E(\Pi_{BS})]^2. \end{aligned} \quad (2)$$

In order to obtain the exact expression of the profit variance, all parts in Equation (2) need to be expressed in analytical forms. The profit variance can be computed (the details are provided in Appendix 2) as follows:

$$\begin{aligned} Var(\Pi_{BS}) &= (r - \mu_s)^2 \sigma_d^2 + (\mu_s - w)^2 \sigma_Y^2 + \sigma_s^2 (\mu_Y^2 + \sigma_Y^2 + \mu_d^2 + \sigma_d^2 + \rho_{d,s}^2 \sigma_d^2 + \rho_{y,s}^2 \sigma_Y^2 \\ &\quad - 2\mu_Y \mu_d) - 2\rho_{d,s} \sigma_d \sigma_s (r - \mu_s)(\mu_d - \mu_Y) - 2\rho_{y,s} \sigma_s \sigma_Y (\mu_s - w)(\mu_d - \mu_Y) \\ &\quad - 2\rho_{d,s} \rho_{y,s} \sigma_d \sigma_Y \sigma_s^2 - 2\rho_{d,y} \sigma_d \sigma_Y [(\mu_s - r)(\mu_s - w) + \sigma_s^2]. \end{aligned} \quad (3)$$

If we substitute $\mu_Y = \mu_y Q$ and $\sigma_Y = \sigma_y Q$ into Equation (3), we find that the highest order of Q is two. Therefore, the equation can be written as a quadratic function $f(Q) = aQ^2 + bQ + c$ ($a \neq 0$, b , and c are constants). Moreover, the coefficient of Q^2 is proved to be positive. Proposition 1 describes in detail the relationship between the profit variance $Var(\Pi_{BS})$ and the order quantity Q .

Proposition 1 *The profit variance $Var(\Pi_{BS})$ has a minimal value and the profit variance $Var(\Pi_{BS})$ will ultimately increase with the increase of the order quantity Q .*

Proof. See Appendix 3.

Thus, if the buyer orders a large number of products from the contract supplier, the expected profit may be high, but the profit variance can be large. The risk-averse buyer

welcomes high expected profits but hates profit variances at the same time. The objective function $Z(Q) = E(\Pi_{BS}) - kVar(\Pi_{BS})$ exactly characterizes this relationship.

The optimal order quantity Q^* is as follows (the detailed derivation process is in Appendix 4):

$$\frac{(\mu_s - w)\mu_y + \rho_{y,s}\sigma_y\sigma_s}{2k} + \frac{\mu_d\mu_y\sigma_s^2 - \rho_{d,s}\mu_y\sigma_s\sigma_d(r - \mu_s) + \rho_{y,s}\mu_d\sigma_s\sigma_y(\mu_s - w)}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w)} + \frac{\rho_{d,s}\rho_{y,s}\sigma_d\sigma_y\sigma_s^2 + \rho_{d,y}\sigma_d\sigma_y[(\mu_s - r)(\mu_s - w) + \sigma_s^2]}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w)}.$$

Based on the analytical expression of the optimal order quantity, we obtain some monotonicity conditions for the optimal order quantity Q^* with respect to the correlation coefficients $\rho_{d,y}$ and $\rho_{d,s}$, as shown in Propositions 2 and 3. Note that when we say that correlation coefficients increase, we mean that their absolute values increase.

Proposition 2 *If the correlation coefficient $\rho_{d,y}$ between demand and yields increases, the optimal order quantity Q^* will*

- (a) *increase if $\sigma_s^2 < (r - \mu_s)(\mu_s - w)$;*
- (b) *decrease if $\sigma_s^2 > (r - \mu_s)(\mu_s - w)$ and*
- (c) *remain unchanged if $\sigma_s^2 = (r - \mu_s)(\mu_s - w)$.*

Proof. See Appendix 5.

Proposition 3 *If the correlation coefficient $\rho_{d,s}$ between demand and spot prices increases, the optimal order quantity Q^* will*

- (a) *increase if $\rho_{y,s} > \frac{\mu_y(r - \mu_s)}{\sigma_s\sigma_y}$;*
- (b) *decrease if $\rho_{y,s} < \frac{\mu_y(r - \mu_s)}{\sigma_s\sigma_y}$ and*

(c) remain unchanged if $\rho_{y,s} = \frac{\mu_y(r-\mu_s)}{\sigma_s\sigma_y}$.

Proof. See Appendix 6.

If all the correlations among uncertainties vanish, the optimal order quantity Q^* reduces to a simple form as follows:

$$Q^* = \frac{\frac{(\mu_s - w)\mu_y}{2k} + \mu_d\mu_y\sigma_s^2}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2}. \quad (4)$$

In uncorrelated environments, Propositions 4 and 5 study the monotonic relationships between the optimal order quantity Q^* and the means of random demand and yields, respectively.

Proposition 4 *If the mean of demand increases, the optimal order quantity Q^* will also increase.*

Proof. See Appendix 7.

Proposition 5 *If the mean of random yields increases, the optimal order quantity Q^* will*

(a) *increase if $(\frac{\mu_y}{\sigma_y})^2 < (\frac{\mu_s - w}{\sigma_s})^2 + 1$;*

(b) *decrease if $(\frac{\mu_y}{\sigma_y})^2 > (\frac{\mu_s - w}{\sigma_s})^2 + 1$ and*

(c) *remain unchanged if $(\frac{\mu_y}{\sigma_y})^2 = (\frac{\mu_s - w}{\sigma_s})^2 + 1$.*

Proof. See Appendix 8.

3.2.2 Other models

In this subsection, three other procurement strategies are considered, including PC, BO and SO. Their strategies and the corresponding models are proposed. In Section 3.3.6,

a simulation-based optimization solution technique for these three strategies will be presented.

In the BS model, the spot market can be used for both buying and selling. In order to show the effects of adopting the spot market, the following three different strategies are also introduced for comparison purposes: pure contract sourcing, the spot market used only for buying and the spot market used only for selling. At time 0, the buyer orders Q units from the contract supplier. At time T , demand d is realized, but the supplier can only deliver Y units because of random yields. If the spot market is not used for selling, the additional $(Y - d)^+$ units of inventory are salvaged with a unit price g . On the contrary, when the spot market is not used for sourcing, unmet demand is lost with a unit price p .

PC: The spot market is neither used for buying nor used for selling. Unmet demand is penalized with the price p and extra inventory is salvaged with the price g . The profit of the buyer is expressed as follows:

$$\Pi_{PC}(Q) = r\min(d, yQ) - wyQ + g(yQ - d)^+ - p(d - yQ)^+. \quad (5)$$

BO: The spot market is used only to meet extra demand and unsold products are salvaged with the price g . The buyer's profit is shown as follows:

$$\Pi_{BO}(Q) = rd - wyQ + g(yQ - d)^+ - s(d - yQ)^+. \quad (6)$$

SO: The buyer uses the spot market only for selling extra inventory. The buyer's profit is provided as follows:

$$\Pi_{SO}(Q) = r\min(d, yQ) - wyQ + s(yQ - d)^+ - p(d - yQ)^+. \quad (7)$$

3.3 Computational study

The following computational study explains the necessity and the benefits of taking yield risks into consideration. Based on the analytical results of the BS model obtained in Section 3.2.1, sensitivity analysis is conducted to analyze the effects of risk aversion, yield COVs, spot price COVs, demand COVs and uncertainty correlations. In Subsection 3.3.6, simulation-based optimization solutions for the three models discussed in Subsection 3.2.2 are presented. The data used in the computational study are summarized in Table 3.1.

Table 3.1: Summary of parameter values

Deterministic parameter			
Sales price per unit	30	Wholesale price per unit	10
Salvage value per unit	8	Risk aversion parameter	0.005
Penalty cost per unit	20	Trials per simulation	100,000
Uncertain parameter			
Yield	Mean $\mu_y = 0.75$	Standard deviation $\sigma_y = 0.05$	
Spot price	Mean $\mu_s = 12$	Standard deviation $\sigma_s = 2.50$	
Demand	Mean $\mu_d = 100$	Standard deviation $\sigma_d = 25$	
Correlation coefficient			
	Yield	Spot price	Demand
Yield	1.00	−0.10	−0.05
Spot price	−0.10	1.00	0.20
Demand	−0.05	0.20	1.00

3.3.1 Effect of risk aversion

A buyer's risk aversion is denoted by the risk aversion parameter. More risk-averse buyers are more sensitive to profit variances. They are not willing to seek additional profits when they are exposed to tremendous profit risks. As shown in Figure 3.1, when the risk aversion parameter increases, the optimal order quantities from both the BS model and Seifert et al. (2004)'s model decrease. One buyer taking yield risks into consideration orders more products than the other one overlooking yield risks. Moreover, we observe that the BS model results in higher expected profits and profit standard deviations than those of Seifert et al. (2004)'s model (when we calculate the expected profits and the profit standard deviations of Seifert et al. (2004)'s model, we plug the derived optimal order quantities from Seifert et al. (2004)'s model into the BS model's expected profit and profit standard deviation expressions). Furthermore, we observe that when the risk aversion parameter increases, both models' expected profits and profit standard deviations decrease.

Figure 3.1: Comparisons under different risk aversion settings

3.3.2 Effect of yield COVs

The extent of a contract supplier's unreliability can be expressed by the mean and the variance of random yields. More unreliable suppliers tend to have smaller yield means and larger yield variances. The advantage of using COV rather than standard deviation directly is that COV is dimensionless and it can better denote the dispersion of a distribution. As shown in Figure 3.2, when the yield COV increases, the optimal order quantity from the BS model decreases while that from Seifert et al. (2004)'s model remains the same. Taking yield risks into consideration results in higher order quantities. Under different yield COVs, the BS model results in higher expected profits and profit standard deviations than those of Seifert et al. (2004)'s model. Moreover, when the yield COV increases, both models' expected profits decrease while their profit standard deviations increase.

Figure 3.2: Comparisons under different yield COVs

3.3.3 Effect of spot price COVs

Spot prices are uncertain and bring about profit uncertainties. Spot price COVs depict the volatilities of spot prices. As shown in Figure 3.3, when the spot price COV increases, the optimal order quantities from both the BS model and Seifert et al. (2004)'s model decrease. Considering yield risks leads to higher order quantities. Under different spot price COVs, the BS model results in higher expected profits and profit standard deviations than those of Seifert et al. (2004)'s model. Moreover, when the spot price COV increases, both models' expected profits decrease while their profit standard deviations first decrease and then increase.

Figure 3.3: Comparisons under different spot price COVs

3.3.4 Effect of demand COVs

Demand uncertainties are an important factor which cannot be ignored. With the utilization of spot markets, excess inventory can be sold while additional shortage can be purchased. However, this brings about profit uncertainties, as spot prices are also unstable. As shown in Figure 3.4, when the demand COV increases, the optimal order quantities

from both the BS model and Seifert et al. (2004)'s model decrease. Incorporating yield risks leads to higher order quantities. Under different demand COVs, the BS model results in higher expected profits and profit standard deviations than those of Seifert et al. (2004)'s model. Moreover, when the demand COV increases, both models' expected profits decrease while their profit standard deviations increase.

Figure 3.4: Comparisons under different demand COVs

3.3.5 Effect of demand, yield and price correlations

In most industries, rising demand usually brings about high spot prices. So, demand and spot prices are positively correlated. Moreover, both the correlation coefficient between yields and demand and the correlation coefficient between yields and spot prices are negative. The procurement decisions are different under various market correlation environments, such as weak (W), medium (M) and strong (S) correlations. In order to show their influences, an experiment is designed to assess their influences in 27 scenarios as shown in Table 3.2. From the table, we observe that the buyer obtains the largest objective function value 992.59 in a weak $\rho_{d,s}$, weak $\rho_{y,s}$ and strong $\rho_{d,y}$ environment

and the smallest objective function value 951.64 in a strong $\rho_{d,s}$, strong $\rho_{y,s}$ and weak $\rho_{d,y}$ environment.

Table 3.2: Correlation coefficient parameter values and results

N o	$\rho_{d,s}$	$\rho_{y,s}$	$\rho_{d,y}$	Q^*	$E(\Pi_{BS})$	$Var(\Pi_{BS})$	$Z(Q^*)$
1	0.05	-0.05	-0.05	163.67	2041.35	212202.72	980.34
2	0.05	-0.05	-0.15	164.72	2042.93	211296.90	986.45
3	0.05	-0.05	-0.25	165.78	2044.51	210383.24	992.59
4	0.05	-0.15	-0.05	164.33	2040.28	212231.45	979.13
5	0.05	-0.15	-0.15	165.39	2041.87	211321.39	985.26
6	0.05	-0.15	-0.25	166.46	2043.45	210403.39	991.43
7	0.05	-0.25	-0.05	164.99	2039.20	212262.09	977.89
8	0.05	-0.25	-0.15	166.06	2040.78	211347.77	984.04
9	0.05	-0.25	-0.25	167.14	2042.37	210425.43	990.24
10	0.15	-0.05	-0.05	139.70	1999.31	208230.49	958.16
11	0.15	-0.05	-0.15	140.76	2000.89	207502.91	963.37
12	0.15	-0.05	-0.25	141.82	2002.46	206767.47	968.62
13	0.15	-0.15	-0.05	140.09	1998.13	208348.33	956.38
14	0.15	-0.15	-0.15	141.15	1999.71	207618.57	961.61
15	0.15	-0.15	-0.25	142.22	2001.29	206880.87	966.88
16	0.15	-0.25	-0.05	140.46	1996.93	208468.08	954.59
17	0.15	-0.25	-0.15	141.54	1998.51	207736.16	959.83
18	0.15	-0.25	-0.25	142.62	2000.10	206996.22	965.11
19	0.25	-0.05	-0.05	115.74	1957.26	200290.59	955.81
20	0.25	-0.05	-0.15	116.80	1958.84	199741.24	960.13
21	0.25	-0.05	-0.25	117.85	1960.42	199184.03	964.50
22	0.25	-0.15	-0.05	115.84	1955.97	200446.81	953.73
23	0.25	-0.15	-0.15	116.91	1957.55	199897.34	958.06
24	0.25	-0.15	-0.25	117.98	1959.13	199339.95	962.43
25	0.25	-0.25	-0.05	115.94	1954.66	200604.20	951.64
26	0.25	-0.25	-0.15	117.02	1956.24	200054.67	955.97
27	0.25	-0.25	-0.25	118.09	1957.83	199497.13	960.34
Correlation coefficient							
		W		M		S	
	$\rho_{d,s}$	0.05		0.15		0.25	
	$\rho_{y,s}$	-0.05		-0.15		-0.25	
	$\rho_{d,y}$	-0.05		-0.15		-0.25	

3.3.6 Multiple parameterized simulations

In order to determine the optimal order quantities for the other three scenarios: PC, BO and SO, multiple parameterized simulations based on Risk Solver are used. The corresponding models of the three strategies are built and validated in spreadsheets. Parameters are assigned for random yields, demand and spot prices. Their correlation coefficients are constructed using Pearson's product-moment correlation coefficients. The order quantity is set to be an input parameter for Monte Carlo simulations. All the parameter values for simulation studies are the same as those in the BS model, which are shown in Table 3.1. In our simulation studies, the number of trials is 100,000. The buyer's profit is the outcome of each simulation run. The expected profit and the profit variance can be automatically computed using Risk Solver. Thus, the objective function value is obtained. In order to determine the optimal order quantity, multiple parameterized simulations are carried out to automatically vary input parameter values. For each specified order quantity, an objective function value is obtained. The input parameter with the maximum objective function value is the optimal order quantity.

The optimal order quantities are calculated under the four different scenarios: BS, PC, BO and SO. These results are categorized into two groups: ignoring yield risks (G_1) and considering yield risks (G_2). Quantity gap rates (QGRs) show the relative differences of the optimal order quantities. Expected profit gap rates (EPGRs) are used to measure the relative differences of expected profits. In order to illustrate the relative differences of profit variances, profit variance gap rates (PVGRs) are computed. The detailed definitions are as follows:

$$\text{QGR} = (\text{Order quantity of } G_2 - \text{Order quantity of } G_1) / \text{Order quantity of } G_1 \times 100\%;$$

$EPGR = (\text{Expected profit of } G_2 - \text{Expected profit of } G_1) / \text{Expected profit of } G_1 \times 100\%$ and

$PVGR = (\text{Profit variance of } G_2 - \text{Profit variance of } G_1) / \text{Profit Variance of } G_1 \times 100\%$.

Table 3.3 shows that all QGRs, EPGRs and PVGRs of the four models (BS, PC, BO and SO) are positive, that is, taking random yields into consideration results in higher order quantities, higher expected profits, and higher profit variances for all four models.

Table 3.3: Comparison analysis of two groups

Group	Model	Q^*	QGR	Expected profit	EPGR	Profit variance	PVGR
G_1	BS	96.00		1930.30		198907.50	
	PC	106.95		1072.12		170772.86	
	BO	62.71		1877.38		202590.25	
	SO	111.28		1178.54		162492.24	
G_2	BS	127.84	33.17%	1977.67	2.45%	204827.98	2.98%
	PC	147.14	37.58%	1875.02	74.89%	232680.88	36.25%
	BO	81.31	29.66%	1925.20	2.55%	290739.06	43.51%
	SO	154.13	38.51%	2009.03	70.47%	186987.52	15.07%

3.4 Summary

Supply uncertainties are one of the main concerns from buyers' perspectives in today's complicated supply chain environments. Facing random yields and uncertain demand, adopting reactive supply via spot markets is a strategic procurement option, as the delivery lead times from spot markets are short and the regulations of spot markets are very rigorous. In this research, closed-form results are provided for determining the optimal order quantity from a contract supplier when a spot market is used for BS. For the other three strategies (PC, BO and SO), multiple parameterized simulations using Risk

Solver are carried out to analyze the optimal procurement decisions. In our models, the correlations between uncertainties (the correlation between demand and spot prices, the correlation between yields and spot prices and the correlation between demand and yields) are also incorporated.

The contributions of this research are as follows: Firstly, an in-depth study about proactive purchase planning via a spot market is conducted. It can be applied for a broad range of commodities, such as electricity, fuel and water. Secondly, apart from considering demand and spot price uncertainties, this research incorporates yield uncertainties and considers all the correlations among yield, demand and spot price uncertainties. Closed-form results are obtained when the spot market can be used for BS. Thirdly, an innovative way of modeling pure contract sourcing and limited spot market functions (buying or selling only via the spot market) is proposed using multiple parameterized Monte Carlo simulations. Particularly, this practical modeling method can be easily carried out by buyers in industry.

There are several future research directions. The optimal decisions obtained in this research are solely based on a single period setting. Therefore, these decisions cannot be directly applied in multiple periods. Instead of considering a single period, further work on how to use a spot market in a multi-period setting can be investigated. Moreover, to model correlation coefficients, this research adopts Pearson's product-moment correlation coefficients, which measure linear dependences. Another research problem that needs to be considered is incorporating a more sophisticated measure to model the dependences between uncertainties. Furthermore, the determination of a portfolio of suppliers can be examined.

Chapter 4

A Decision Support System for Procurement Risk Management in the Presence of Spot Market

According to the research gaps in Chapter 2, there are limitations of existing methods for modeling multiple correlated risks to support decision makers for allocating orders among multiple suppliers in the presence of spot market and to control lead time uncertainty of delivery. This chapter presents a decision support framework to model risks for procurement processes and to design a robust purchasing plan, including optimal ordering decision and delivery arrangement. Taking advantages of the contract supplier and the spot market, the buyer can better meet business requirements in this dynamic business environment. The findings of reactive sourcing using spot market in Chapter 3 are also adopted and incorporated into the PRM framework.

4.1 Introduction

In order to assist PRM decision making, a novel PRM framework is proposed. The proposed framework helps to generate a procurement plan which includes 1) the set of suppliers should be selected; 2) the order allocation for the respective supplier; 3) the

aggregate order to be purchased from the selected supplier pool; 4) the total order amount from spot market and 5) whether the delivery should be arranged by the purchasing company itself or outsourced to the supplier.

This chapter is organized as follows: Subsection 4.1 describes the problem scenario in detail and related previous study. Subsections 4.2 to 4.5 present the integrated framework from procurement risk identification to risk monitoring. In Subsection 4.6, conclusions are drawn.

4.1.1 The proposed PRM decision support system

The proposed PRM framework provides a novel PRM solution, which includes four stages: (1) procurement risk identification; (2) procurement risk including the supplier risk assessment and delivery arrangement assessment; (3) procurement risk mitigation including the utilization of supplier diversification, reactive sourcing and the comparison analysis for delivery arrangement decision making and (4) procurement risk monitoring. Figure 4.1 depicts the flowchart of the PRM framework.

In the PRM framework, all potential suppliers are found out and the supply risks are identified, such as unpredictable demand, volatile price and uncertain supply yield. Based on the identified risks and the cost components of the procurement, a profit model is built to simulate the performance (expected profit and SaR) of each of the potential suppliers. An algorithm is derived to calculate profit and SaR of each supplier, and only qualified suppliers from the supplier's pool are selected. The goal programming model helps to obtain the order proportions among the selected supplier pool by achieving the objectives and considering related constraints. After knowing the proportion of the order assigned to individual suppliers, the mean of supplier portfolio yield and average wholesale price can

be computed. The analytical result of the contract-spot allocation model is described in detail in Chapter 3, the total amount of products purchased from both contract supplier and spot market are found out, respectively. Thus, the detailed order allocation plan is formulated based on the total purchased amount and the order shares. At the same time, costs and lead time are calculated based on different delivery arrangement choices; a wise choice is selected based on the outcome of different choices' performances.

4.1.2 Research implications

Based on the review of related study on reactive risk management, researchers have already extensively studied both the effectiveness of supplier diversification to reduce supply volatility as well as applying spot market to manage demand uncertainty. However, limited research works have been carried out by adopting both reactive supply and multiple contract suppliers for yield uncertainty management. The incorporation of yield uncertainty into procurement decision making makes the supply more reliable and effective. Taking the advantages of both risk diversifications from a supplier portfolio and spot market, this research manages to solve the problem of order allocation among multiple suppliers in the presence of spot market. Uncertain demand, volatile spot price and unreliable supply are considered in the problem formulation. Moreover, the risk attitude of the buyer will be also incorporated in the proposed model. Generally, two broad areas are related to our research: supplier diversification under yield uncertainty and procurement in the presence of spot market.

Figure 4.1: Framework of the integrated PRM solution

In addition, there is a lack of method to quantify the multiple dimensional and correlated risks when selecting suppliers. Some paper suggests using Analytic Hierarchy Process (AHP) to model the multiple dimensions of supply risks (Ghodsypour and O'Brien, 1998; Kull and Talluri, 2008). But AHP fails to express the correlation among risks which actually exist in the industry. For example, Kull and Talluri (2008) assess the

delivery, cost, quality and flexibility risks using AHP. But the problem is that AHP is incapable of taking risk dependences into consideration. In addition, although there are numerous research works about developing the sourcing model under demand uncertainty, there is lack of research work about order allocation among supplier in the presence of spot market and demand, yield and spot price uncertainties. Without solving these gaps, it is difficult to implement an effective and practical PRM solution.

4.2 Procurement risk identification

At the beginning of procurement workflow, the buyer tries to find out all the potential suppliers from both local and overseas. Each of these long term contract suppliers are different in terms of the price and supply uncertainty. Their supply uncertainty may be caused by different factors such as limited production capability or poor quality control of supplier. In the presence of spot market, the supplier may deliver partially but sell the inventory to the spot market if he or she observes that the spot market's price is quite high (Haksöz and Kadam, 2009). At the same time, spot market is adopted by the buyer as RPRM to meet extra demand or sell the surplus items, but this will lead to risk of volatile spot prices for the procurement model. In addition, the unstable demand from the downstream customer is also difficult to be predicted (Hazra and Mahadevan, 2009). According to Haksöz et al. (2008), the challenges of procurement are to control demand, price and supply uncertainties. Besides, the risk attitude of the buyer also affects the procurement decision. A more risk-averse buyer tends to control risk instead of caring more profits. Therefore, the risk attitude of buyer is also considered in our model. Figure 4.2 illustrates the possible risks associated with multiple suppliers in the presence of spot market.

As shown in Figure 4.2, potential risks include yield and lead time uncertainties from forward contract suppliers, and uncertain spot price and demand from the downstream. Before suitable risk assessment and mitigation methodologies are used, it is necessary to understand more details about these potential risks, such as the risk impact, probability and the detection ability of the risk.

Figure 4.2: Multiple suppliers sourcing in the presence of spot market under uncertainties

4.2.1 Defining the SCR-FMEA risk identification methodology

Successful risk management plan needs to be formulated into several stages. A number of factors are taken into consideration for risk analysis with Supply Chain Risk – Failure

Mode and Effects Analysis (SCR-FMEA). SCR-FMEA (Carbone and Tibbette, 2009) is developed to explore and diagnose the problem at progressive stages.

In stage one, risk events need to be identified, explored and examined in supply chain outsourcing. Hence, the domains of Risk ID and Risk Events in SCR-FMEA are defined. Stage two emphasizes that an important part of risk analysis is to quantify the risks and hence accounts for the domains of risk components such as risk probability factor, impact factor and detection factor in SCR-FMEA. In stage three, it is essential to state all risks consequence for a common understanding of the impact that each risk entails. An understanding of the consequences is crucial for strategy formulation to minimize the negative impacts of risk under recommended risk mitigation domain. In stage four, the decision of managing a certain kind of risk is made. The SCR-FMEA is a qualitative method to document and mitigate supply chain risks.

4.2.2 The designing of SCR-FMEA

A successful supply chain depends on a great extent of risk identification. Occurrence of risk can lead to undesirable consequence and disruption for the supply network. The Failure Mode and Effects Analysis (FMEA) is one of the important planning tools to analyze the cause and consequence of failure. This proposed methodology applies the FMEA format (i.e. failure modes for occurrence, severity and detection) to quantify, analyze and aid risk contingency planning for risks in the supply chain. It can be coined as SCR-FMEA since this method is modified based on the known FMEA technique. Before SCR-FMEA is implemented, the potential risk is identified and listed within each project phase. During this risk identification stage, risk events are recognized. The impact can be in the form of bad reputation, customer dissatisfaction, reduce in revenue or increase in

expense. One risk event can lead to adverse consequence and bring up multiple impacts. The risk score is based on probability of risk, detection and impact shown in Figure 4.3.

Figure 4.3: Relation of risk event and its risk score

FMEA and SCR-FMEA are different in defining the attribute of detection. FMEA's highest detection value means the firm has no ability to detect risk while a low detection value means the firm can find out the risk. In SCR-FMEA, Detection is defined as “the ability of detection technique or method(s) to detect the risk event with enough time to plan for a contingency and act upon the risk” and detection factor is defined based on Carbone and Tippett (2004). Figure 4.4 illustrates a modification from the standard FMEA and the SCR-FMEA.

Sample FMEA Headings						
Failure ID	Failure Mode	Occurrence	Severity		Detection	RPN = Occurrence * Severity * Detection

Sample SCR-FMEA						
Risk ID	Risk Event	Risk Probability	Impact	Risk Score = Risk Probability * Impact	Detection	RPN = Occurrence * Severity * Detection

Figure 4.4: Headings of a sample standard FMEA vs. designed SCR-FMEA

Risk understanding and identification include the step of assessing the risk probability, impact, and detection domain of each risk event. The guidelines on assigning risk probabilities, impact factors and detection factors can be found in Table 4.1.

The scores may require additional data from experts or a review of past FMEA. The quality of the risk analysis done by SCR-FMEA will be greatly increased if inputs on assigning scores are taken from experienced supply chain professionals. The scoring procedure is replicated for the impact and detection factors. The risk probability multiplied by the risk impact value is expanded by multiplying a detection value for each risk. Once the factors for each of the three factors are entered, both the risk score and the Risk Priority Number (RPN) values are calculated based on the formulas:

$$\text{Risk score} = \text{Risk Probability} \times \text{Impact}$$

$$\text{RPN} = \text{Risk Probability} \times \text{Impact} \times \text{Detection}.$$

4.2.3 Critical procurement risks ranking using RPN map

A Pareto chart is generated based on their risk scores tabulated in descending order. This chart provides guidance for prioritizing risk response planning. The RPN Pareto bar chart is plotted which contains RPN values in descending order. As supply chain of each firm is unique, the risk and the corresponding risk score and RPN values may vary. A risk map diagram shown in Figure 4.5 which constitutes of a scatter plot of RPNs against risk scores generated. Firms should put more resources to mitigate those risks which are identified as high RPN and high score (located at the right top corner of the risk map). In our PRM study, we mainly focus on four major risks as reported in the industry and academic: demand risk, uncertain yield, spot price uncertainty and delivery uncertainty. After calculating the risk score and RPN for all these possible risks identified, purchasing

department have a more clear picture of the impacts and detection of the possible risks. In our study, the risk map is limited to demand, yield, uncertain spot price and lead time risks based on our needs. But this map can be directly applied to other cases where a large number of risks involved.

4.3 Procurement risk assessment

In Subsection 4.2, the most important and critical risks are explored and identified, the buyer can proceed with the supplier risk assessment and delivery arrangement risk assessment if required, based on the methodologies introduced in Subsection 4.3.1 and Subsection 4.3.2, respectively. The risk assessment methodologies are designed to cover all the above mentioned risks. However, if certain kinds of risk are not essential based on the result of risk identification, this risk factor can be ignored by assigning a deterministic value to it instead of an uncertain variable.

Table 4.1: Risk probability factors, impact factors and detection factors in SCR-FMEA

Number	Risk Probability Factors	Detection Factors	Impact Factors
9 to 10	80% to 100% chance of occurrence. Circumstances frequently encountered daily, weekly and monthly	Detection method is highly effective and it is almost certain that the risk will be detected with adequate time	Very major loss of service; Bad reputation; Cost increases >20%
7 to 8	60% to 80% chance of occurrence Regular occurrence few times a year	Detection method has moderately high effectiveness	Complete loss of important service for short period; Adverse publicity of major nature; Customer dissatisfaction, Cost increases 10%-20%
5 to 6	40% to 60% chance of occurrence. Likely to happen at some point within 1-2 years	Detection method has medium effectiveness	Service Disruption =4-5 days; Statutory prosecution of non-serious nature; Severe loss of revenue; Cost increases 5%-10%
3 to 4	20% to 40% chance of occurrence, only likely to happen 3 or more years	Detection method is unproven or unreliable; or effectiveness of detection method is unknown to detect in time	Brief disruption of important service area; Adverse local publicity; Lower productivity; Cost increases 0%-5%
1 to 2	< 20% chance of occurrence Has never or rarely happened before	There is no detection method available that will provide an alert with enough time to plan for a contingency	Service Disruption = 1 day; Contained within department; Cost increases insignificantly

Figure 4.5: Risk map of RPN against risk score

4.3.1 Supplier risk assessment based on Profit-SaR matrix

After identifying three most important risks related to optimal ordering decision in the presence of spot market, risk assessment is carried out with Monte Carlo simulation.

Monte Carlo simulation (using random sampling) is a well-established method for evaluation of risk. It is basically a sampling experiment whose purpose is to estimate the distribution of an outcome variable that depends on simulation of several probabilistic inputs variables to compute their results (Evans and David, 1998). Assumptions about the uncertainty of key inputs are made and this uncertainty is characterized by specifying probability distributions for these model inputs. Different values of each factor are inputted into the spreadsheet model and with different combination of inputs; a distribution of possible values is set up to provide an indication of the likelihood of what practitioners might expect.

A mathematical model which determines the level or a specific type of risk by involving parameters is built and it contributes to the different type of risk. As risks are inherently present in the outsourcing project, the identification of critical risks is crucial due to the high level of impact that entails to finances of the company. Hence, a modeling environment which is well supported by Monte Carlo simulation is necessary and it will concentrate on the pre-stages of the outsourcing project.

In order to build the simulation model, the components of the profit and cost of procurement need to be found out, such as the sales revenue, purchasing cost, penalty cost for not meeting demand, salvage value for extra inventory and fixed cost for purchasing. Let's denote sales revenue sources by $R_1, R_2, \dots, R_m$ (m is the number of possible revenue sources or ways to add value) and other cost components as $C_1, C_2, \dots, C_n$ (n is the number of possible costs categories). The profit of buyer Π_{buyer} purchasing from supplier i is expressed as:

$$\Pi_{buyer} = f_i(R_1, R_2, \dots, R_m; C_1, C_2, \dots, C_n).$$

The simulation model can be implemented using .NET, Java, Matlab, Visual Basic and other languages with Solver SDK Platform, which is a comprehensive software development kit for developing applications using optimization and Monte Carlo simulation. A list of available distributions included in Solver SDK is presented in Table 4.2.

Table 4.2: Available distributions in Solver SDK platform

Distribution Category	Distributions
Continuous Analytic Distributions	Beta; BetaGen; Cauchy; ChiSquare; Erf; Erlang; Exponential; Gamma; InvNormal; Laplace; Logistic; LogLogistics; LogNormal; LogNom2; MaxExtreme; MinExtreme; Myerson; Normal; Pareto; Pareto2; Pareson5; Pearson6; Pert; Rayleigh; Student; Triangular; Uniform; and Weibull,TriangGen.
Discrete Analytic Distributions	Bernoulli; Binomial; Geometric; HyperGeo; IntUniform; Logarithmic; NegBinomial; Poisson;
Custom Distributions	Cumul; Discrete; DisUniform; Genearl; and Histogram.
Stochastic Information	Creating SIP from data source or distribution

According to the actual situation, distribution can be chosen from the list in Table 4.2 for every uncertain variable. Then the correlations among variables can be denoted by the Spearman rank order correlation matrix. The Spearman rank correlation coefficient is used to induce dependency between any two uncertain variables, whether they are both from analytical distribution or even custom distribution. The value of the coefficient ranges from -1 to 1 . The coefficient $r_{x,y}$ between random variable x and y can be computed from the sample values $x[]$ and $y[]$ over n trials in Monte Carlo simulation as:

$$r_{x,y} = \frac{n \sum_{i=1}^n x_i y_i - (\sum_{i=1}^n x_i)(\sum_{i=1}^n y_i)}{\sqrt{[n \sum_{i=1}^n x_i^2 - (\sum_{i=1}^n x_i)^2][n \sum_{i=1}^n y_i^2 - (\sum_{i=1}^n y_i)^2]}}$$

After assigning values to all the risk variables and constructing the correlations among them, the model can be solved by calling a Monte Carlo simulation engine in the Solver SDK. Based on the output of the model, two values can be calculated: expected profit and SaR. The concept of SaR is similar as the VaR concept in finance applications. VaR is used to show the maximal loss that can occur at a given confidence level. SaR is the profit

at risk for the uncertain profit function at a specified confidence level, which can also be expressed as percentile (e.g., 0.95 or 0.99).

The above procedures of Monte Carlo simulation are implemented using C#.NET based on the Solver platform. The following is the pseudo code of the simulation algorithm which is named as Expected Profit – Supply at Risk (A-EPSaR).

The pseudo code of A-EPSaR

```

Main function ()
{
    Initialize the number of uncertain variables nvars;
    Calculating the correlation coefficients and construct the correlation matrix correl;
    Create instance of the Problem class: Problem = new problem
    (Solver_Type.Simulate, nvars, nfcns);
    Pass the distribution to uncertain variables;
    Create the simulation evaluator and pass the Evaluator function values to the SDK;
    Tell the SDK to continue simulation until the trial number is reached;
    Save the values of Expected profit and SaR for each supplier.
};

Evaluator function ()
{
    Create a pointer p to the Problem: Problem p = evaluator. Problem;
    Create a pointer pVar to uncertain values;
    The uncertain profit function:
     $\Pi_{buyer} = f_i(R, C_1, C_2, \dots, C_n) = F(pVar_1, pVar_2, \dots, pVar_{nvars}).$ 
}.

```

In order to better configure and optimize the supply base, the performance of each potential supplier is evaluated with the simulation algorithm A-EPSaR. For the

standardization of the profit index and SaR index, the values of the outputs are normalized. The normalized expected profit and SaR are then used to classify suppliers into three groups: preferred supplier, approved supplier and avoided supplier. Preferred suppliers are those suppliers who can help the buyer to achieve a high level of expected profit with a low level SaR risk; Approved suppliers are those suppliers who have medium level expected profit and risks; An avoided supplier's performance in terms of profit and risk is the worst among the three groups, i.e. low profit but high risk. Similar classification method for suppliers is also found in Gosling et al. (2010), in which suppliers are grouped under three categories based on sourcing flexibility. Figure 4.6 shows the classification of potential supplier based on the proposed Profit-SaR Matrix.

Figure 4.6: Profit-SaR Matrix

From Figure 4.6, it is easy to observe that some of the suppliers are less favorable than others. For instance, the type of preferred supplier is definitely better than avoided supplier. In order to remove suppliers whose performances are worse than others, pairwise comparisons are conducted among the potential suppliers. For example, if

supplier A 's expected profit is less than that of supplier B and the SaR of supplier A is larger than supplier B , supplier A should then be removed from the supplier pool. Based on the result of pairwise comparisons, the suppliers whose performances are inferior to others are deleted from the supplier's pool and a selected supplier pool P^* is obtained. From the Figure 4.6, it is easy to observe that some of the suppliers are strictly dominated by others. For instance, the type of preferred supplier will definitely dominate avoided supplier. An algorithm named as A-RDSS (Remove Dominated Supplier from Supplier Pool) is designed to remove those dominated suppliers from the supplier's pool.

The pseudo code of A-RDSS

```

Initialize: Counter  $i = 0$ ; Counter  $j = 0$ ; Supplier pool  $P$ ;
WHILE Counter  $i < \text{The number of suppliers}$ 
  Counter  $j = \text{Counter } i + 1$ ;
  WHILE Counter  $j < \text{The number of suppliers}$ 
    IF Expected profit of  $P_i < \text{Expected profit of } P_j \text{ and } SaR_i > SaR_j$ 
      Remove supplier  $i$  from the supplier pool  $P$ 
    ELSE
      Keep supplier  $i$  in the pool
  Return the optimal supplier pool  $P^*$ 

```

4.3.2 Delivery risk assessment

Delivery arrangement for the ordered products can be one of the risk events and lead time uncertainty is one of the concerns for purchasers. This means whether lead time risk is with high RPN and risk score. The quantitative risk assessment will help to decide whether the delivery should be outsourced to/handled by the supplier or the procurement department should control it by itself. Related risk measurements are identified and then

simulation models are developed based on these risk measurements. In this subsection, the procedures of how to perform Monte Carlo Simulation using Risk Solver are described in detail. The output from the simulation study can be used to help companies to analyze the delivery performances before and after outsourcing.

One of the essential responsibilities of management team is to meet the company's strategic mission. In order to achieve the goal, it is common to have performance indicators to help monitor the progress and evaluate its performance. The commonly used performance indicators in delivery are total estimated delivery lead time and total estimated delivery cost. The mathematical models for quantitative risk assessment should also adhere to these performance indicators.

Each performance indicator can be further divided into small components. The lead time components $L_1, L_2, \dots, L_n$ are functions of total delivery lead time.

$$\text{Total Estimated Delivery Lead Time} = f(L_1, L_2, \dots, L_n);$$

The estimated delivery cost components $C_1, C_2, \dots, C_n$ are functions of total estimated cost.

$$\text{Total Estimated Delivery Cost} = f(C_1, C_2, \dots, C_n);$$

After risk management strategy is adopted, the corresponding lead time and cost are as follows:

$$\text{Total Estimated Delivery Lead Time} = f(L_1, L_2, \dots, L_n)_{After};$$

$$\text{Total Estimated Delivery Cost} = f(C_1, C_2, \dots, C_n)_{After};$$

Total Estimated Delivery Cost Savings equals to:

$$\frac{f(C_1, C_2, \dots, C_n)_{After} - f(C_1, C_2, \dots, C_n)_{Before}}{f(C_1, C_2, \dots, C_n)_{Before}}.$$

After developing the simulation model, Monte Carlo simulation is used to assess the risk and cost. To perform a Monte Carlo simulation, the formula mentioned above is set in spreadsheet as shown in Figure 4.7. The next step is to identify inputs for the proposed model which is uncertain and use PSI Distribution function or random variables (uncertain variables) to represent the uncertain inputs. Then the output values are generated by Risk solver based on the mathematical model. The above steps are repeated for a sufficient number of times to create a distribution of results. Statistics summary is generated and output data is collected in frequency distribution for further analysis.

Figure 4.7: Risk assessment model on spreadsheet

4.4 Procurement risk mitigation

Based on the risk assessment results of suppliers and delivery choices, supplier diversification and reactive sourcing strategies are proposed to mitigate risks related to ordering decision in Subsection 4.4.1 and Subsection 4.4.2, respectively. Moreover, a comparison analysis in Subsection 4.4.3 is conducted to help decide whether it is wise to

ask supplier to be responsible of the delivery or to control the delivery by the purchasing department itself.

4.4.1 Supplier diversification for the optimal ordering decision making

Supply risk assessment enables us to get a selected supplier pool P^* from the original supplier pool. At the beginning of every period, the buyer orders Q_i units from the contract supplier i ($i = 1, 2, \dots, N$) in the selected supplier pool P^* . At the end of every period, demand d is realized, but the supplier i could deliver only Y_i units because of random yield. If $\sum_{i=1}^N Y_i$ is larger than demand d , the buyer will use the spot market to sell $(\sum_{i=1}^N Y_i - d)^+$ units at the unit price s . On the other hand, if $\sum_{i=1}^N Y_i$ is smaller than demand d , spot market will be used for buying $(d - \sum_{i=1}^N Y_i)^+$ units at price s . Figure 4.8 shows the decision making process of procurement in a single period.

Figure 4.8: The purchasing process in a single period

The following is a summary of related notations:

Random yield of supplier i ($i = 1, 2, \dots, N$) y_i : Normal random variable with mean μ_i and standard deviation σ_i ;

Random yield of the optimal supplier pool y : Normal random variable with mean μ_y and standard deviation σ_y ;

d : Demand is assumed to be a normal random variable with mean μ_d and standard deviation σ_d ;

Spot market price s : Normal random variable with mean μ_s and standard deviation σ_s ;

r : Final value per unit;

w_i : Wholesale price from supplier i ;

w : Average portfolio wholesale price paid to the supplier per unit;

k : The buyer's risk aversion parameter;

$\rho_{d,s}$: Correlation coefficient between demand and spot price;

$\rho_{y,s}$: Correlation coefficient between yield and spot price;

$\rho_{d,y}$: Correlation coefficient between demand and yield;

p_i : The order allocation share for supplier i ;

x_i : 1 or 0, if supplier i is selected, $x_i=1$;

$d_j^{-/+}$: The deviation with the ideal objective;

ω_j : The weight of the j^{th} objective;

M : A large value to balance the inconformity of data and

FC : The fixed cost of doing business with an additional supplier.

The function of the goal programming model is to calculate the order proportions among the selected suppliers in the pool P^* . Supposing that supplier i ($i = 1, 2, \dots, N$) is allocated p_i percentages in a single period. The wholesale price of supplier i is w_i with fixed cost FC . A goal programming model for aiding order proportions decision making in a single period is built as follows:

Objective function: The objective of this optimization model is to figure out the optimal order shares among the selected supplier pool to obtain the minimal cost at the lowest risk level in a single period. The cost contains the purchasing cost of products $\sum_{i=1}^N p_i w_i$ and the total fixed cost of buying from selected contract suppliers $\sum_{i=1}^N x_i FC$. The weight of ω_j denotes the importance of objective j based on the buyer's judgment. x_i equals to 1 or 0. At the same time, the SaR score is minimized and expected profit score is maximized.

$$\text{Min} \sum_{i=1}^N p_i w_i + \sum_{i=1}^N FC x_i + M \sum_{j=1}^J \omega_j d_j^{-/+}.$$

Goal 1: To minimize the SaR (supply at risk): SaR_i is the SaR risk score of supplier i . SaR^{+*} is the best score. The objective is met by reducing the underachievement of SaR^{+*} .

$$\sum_{i=1}^N SaR_i x_i - SaR^{+*} \sum_{i=1}^N x_i + d_1^- = 0.$$

Goal 2: To maximize the expected profit score: EP_i is the profit's risk score of supplier i . EP^{-*} is the worst performance score in terms of expected profit. The objective is met by maximizing the overachievement of EP^{-*} .

$$\sum_{i=1}^N EP_i x_i - EP^{-*} \sum_{i=1}^N x_i - d_2^+ = 0.$$

Constraint 1: Demand should be satisfied:

$$\sum_{i=1}^N p_i - 1 = 0.$$

Constraint 2: With the aim of diversifying risks among the selected supplier pool, the order proportion assigned to a single supplier should be bigger than p^{Min} and small than p^{Max} :

$$p_i = \begin{cases} 0, & x_i = 0; \\ p_i, & x_i = 1. \end{cases} \quad \text{and} \quad p^{Min} \leq p_i \leq p^{Max}.$$

The above constraint can be expressed as the following form and it is solvable by linear programming software:

$$p_i - x_i p^{Min} \geq 0;$$

$$p_i \leq x_i p^{Max}.$$

The order allocation model based on goal programming will generate an optimal order proportion among the supplier pool P^* for a single period. The optimal plan is expressed as $p^*(p_1^*, p_2^*, \dots, p_N^*)$. Supposing that the total amount of products purchased from contract suppliers in a certain period is Q^* , the optimal order quantity Q_i^* from supplier i equals to $Q^* p_i^*$.

4.4.2 Reactive sourcing for the optimal ordering decision making

The goal programming methodology introduced in Subsection 4.4.1 helps to allocate the order among multiple suppliers based on the supplier diversification. In this subsection, the results of order allocation between forward contracts and spot market is given directly. The detailed calculation process is quite long and can be found in Chapter 3.

In order to obtain the total order quantity Q^* for a certain period, for the entire selected contract supplier pool, the yield mean, yield standard deviation and average wholesale

price need to be determined first. As contract suppliers are assumed to be independent with each other, the portfolio yield and wholesale price can be expressed as:

The yield mean of the selected portfolio of suppliers: $\mu_y = \sum_{i=1}^N p_i^* \mu_i$;

The yield standard deviation of the selected portfolio of suppliers: $\sigma_y = \sqrt{\sum_{i=1}^N p_i^{*2} \sigma_i^2}$;

and

The average wholesale price of the selected portfolio of suppliers: $w = \sum_{i=1}^N p_i^* w_i$.

Based on the result of contract-spot allocation model in Chapter 3, the total number of products purchased from contract suppliers Q^* in a single period can be calculated by inputting all the related parameters of the selected supplier pool and spot market.

$$Q^* = \frac{\frac{(\mu_s - w)\mu_y + \rho_{y,s}\sigma_y\sigma_s}{2k} + \mu_d\mu_y\sigma_s^2 - \rho_{d,s}\mu_y\sigma_s\sigma_d(r - \mu_s) + \rho_{y,s}\mu_d\sigma_s\sigma_y(\mu_s - w)}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w)} + \frac{\rho_{d,s}\rho_{y,s}\sigma_d\sigma_y\sigma_s^2 + \rho_{d,y}\sigma_d\sigma_y[(\mu_s - r)(\mu_s - w) + \sigma_s^2]}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w)}.$$

Therefore, the optimal order quantity Q_i^* from contract supplier i is $Q^*p_i^*$.

4.4.3 Comparison analysis for delivery arrangement decision making

By comparing the results of the two delivery arrangements, buyers can determine whether the delivery should be controlled by themselves or suppliers. Table 4.3 illustrates the four possible scenarios and the corresponding risk management actions.

Table 4.3: Delivery outsourcing risk management plan

No.	Scenarios	Actions
1	$\text{Total cost}_{(\text{after outsourcing})} > \text{Total cost}_{(\text{before outsourcing})}$ $\text{Total lead time}_{(\text{after outsourcing})} > \text{Total lead time}_{(\text{before outsourcing})}$	Arranged by the purchasing department itself
2	$\text{Total cost}_{(\text{after outsourcing})} > \text{Total cost}_{(\text{before outsourcing})}$ $\text{Total lead time}_{(\text{after outsourcing})} < \text{Total lead time}_{(\text{before outsourcing})}$	To be determined based on differences
3	$\text{Total cost}_{(\text{after outsourcing})} < \text{Total cost}_{(\text{before outsourcing})}$ $\text{Total lead time}_{(\text{after outsourcing})} > \text{Total lead time}_{(\text{before outsourcing})}$	To be determined based on differences
4	$\text{Total cost}_{(\text{after outsourcing})} < \text{Total cost}_{(\text{before outsourcing})}$ $\text{Total lead time}_{(\text{after outsourcing})} < \text{Total lead time}_{(\text{before outsourcing})}$	Outsourced to the supplier

4.5 Procurement risk monitoring

Both suppliers' performances and market environment will affect the decision of the optimal procurement plan. In order to ensure the resilient of supply, buyers should keep track of the changing of market environment (e.g., spot price movement) and the performance of potential suppliers (e.g., individual wholesale price and yield), so as to update the procurement plan period by period.

4.6 Summary

Chapter 4 illustrates the novel PRM framework which includes procurement risk identification, risk assessment, risk mitigation and risk monitoring. Corresponding methodologies are also explained in detail. This combination approach involves a

qualitative risk analysis methodology termed as the SCR-FMEA for risk identification. And Monte Carlo simulation algorithm named as A-EPSaR is proposed to quantify each supplier's risk so as to let decision maker realize the trade-off between profit and risk. The goal programming model helps to allocate orders among the supplier pool and the contract-spot allocation model can assign orders between the spot market and the supplier pool, respectively. Delivery outsourcing decision making is supported by the simulation model implemented via Risk Solver. The significance of this chapter is the proposed novel decision support framework which helps the buyer to make optimal and robust procurement decision including supplier selection and order allocation among multiple supplier sources in the existence of correlated demand, yield and spot price uncertainties.

Chapter 5

Case Study

In the previous chapter, a novel PRM framework is introduced to help make optimal ordering and delivery arrangement decisions. In this chapter, a case study is used to explain how to use the previous proposed methodologies to solve real industry problems.

Subsection 5.1 introduces the procurement business process and the case scenarios. Procurement risks are explained in Subsection 5.2. Then in Subsections 5.3 and 5.4, optimal ordering decision and delivery arrangement case studies are conducted, respectively. In the last subsection, a summary is provided.

5.1 The Procurement business process

In a manufacturing company, procurement is an important business support function. The main responsibilities of the buyers in procurement department include purchasing requested items and arranging delivery. The performances of the buyers can greatly affect the manufacturing schedule and the final costs of the products. In this case study, a common procurement business process is introduced and problems are identified. In order to better describe the problem, a common work flow process is depicted in the following Figure 5.1.

Figure 5.1: A common procurement workflow in the procurement department

The buyer receives a purchasing request from the manufacturing department on April 1st and is required to make sure items are delivered to the manufacturing department before the beginning of May. During the following business day April 2nd, the buyer will first search from the procurement database and find purchasing historical transactions with same items. Emails will be sent to these suppliers and suppliers are asked to submit their quotations with price and lead time. By April 5th, suppliers are required to reply the quotation emails with their offered price and lead time. By April 7th, the buyer will select suitable suppliers and allocate orders among the selected suppliers based on his/her experiences. During this process, the buyer's personal risk aversion will also affect the

decision making. The procurement department will decide whether the delivery should be arranged by itself or outsourced to the supplier at this stage. Then after about three weeks around April 27th, items will be delivered to the manufacturing department for quality checking. On April 28th, the quality assurance team will check the delivered items and see whether they have reached the required quality standard or not. After all this is done, procurement and delivery related information will be passed to finance department. As a common practice in the industry, suppliers will be paid three months later around August 1st. Figure 5.2 is a purchasing forward contract order example and some of the items are marked according to the confidential policy.

PO No. : PO/070520/10

Tel: 62653300, Fax: 62596355
UEN No: 197602325K

CONFIRMATION ORDER

Date: 2010/03/29

Vendor Code 86345		Vendor Name [REDACTED]		Facsimile [REDACTED]		Address Room 1102-03, 11/F., Kowloon Building, 555 Nathan Road, Mongkok, Kowloon, Hong Kong Shipping Address 1004, Toa Payoh North, #03-10, Singapore 318995	
Contact Person	Telephone	HandPhone	Email				
[REDACTED]		[REDACTED]		[REDACTED]		[REDACTED]	

PR No PR/10/062626	Supervisor [REDACTED]	Requestor [REDACTED]	Department [REDACTED]	
Category M	Cost Code 61-046-03	Terms 30 days	Ship Via [REDACTED]	Shipping Terms EX FACTORY
			Buyer [REDACTED]	

*NOTE:

YOU ARE REQUIRED TO ACKNOWLEDGE AND ACCEPT THIS ORDER . YOUR ACCEPTANCE ARE TO BE GIVEN TO TRIO -TECH WITHIN 7 DAYS OF RECEIPT OF THIS ORDER . TRIO-TECH SHALL BE DEEMED TO HAVE SO CONSENTED TO THE TERMS & CONDITIONS FROM OUR PURCHASE ORDER HEREIN IF THE ACKNOWLEDGEMENT IS NOT RECEIVED WITH SAID 7 DAYS.

Work Order	Description
90133--	DIODE, SMT SS26T3, 2A 60V, SMB PN:SS26T3G DC:08+ SPQ:2500/REEL MOQ:5000PCS
Brand	Part No. (Supplier) Part No. (Internal) Req Dely Date Actu al Qty Unit Price Disc Price Curr Exchg Rate Total Amt
ON SEMI	SS26T3 [REDACTED]

Total Amount : [REDACTED]

* This is a computerised generated document, no signature is required for this document.

Figure 5.2: A forward contract example

Based on the above procurement business process, we find the following questions needs to be answered so as to better serve the needs from the manufacturing department.

Optimal Ordering Decision Making:

- Question 1: What should the company do if the delivered components are not enough or more than needed?
- Question 2: How does the buyer the order among different supplier sources?
- Question 3: How does the buyer's risk aversion affect the order quantity?

Solution: To utilize the methodologies in PRM framework to obtain optimal ordering decision: Supplier diversification and reactive sourcing from spot market are adopted, and related risk factors are considered and studied in the model.

Delivery Outsourcing Decision Making:

- Question 4: How does the company decide whether the delivery should be outsourced to supplier or not?

Solution: Use the simulation model based on Risk Solver to compare the performances of the two choices: outsourcing delivery to supplier or taking charge of it by the purchasing department.

5.2 Procurement risks in the semiconductor industry

With the fast development of technology, semiconductor industry is changing very fast. New products and technologies come out very quickly. This competitive business environment requires companies to be prepared for the risks. Table 5.1 illustrates some of the most important risks that semiconductor industry faces and the corresponding impacts on the firms.

Table 5.1: Major procurement risks and consequences in the semiconductor industry

No.	Risk	Consequence
1.	Demand Fluctuations	The semiconductor industry develops very fast and experiences heavy demand fluctuations, which affects the entire supply chain thereby affecting the procurement decisions of a firm.
2.	Spot Price Fluctuations	Price is controlled by the market and it is not possible for small and medium players to get a deterministic spot price for reactive sourcing.
3.	Uncertain Yield	It is often the case that suppliers cannot deliver enough components to the purchasing company. This will have heavy impacts on the manufacturing, such as the delay of production and product supply.
4.	Lead Time Uncertainty	The lead time is comprised of several stages of delivery. The uncertainty of lead time will have negative impacts on the manufacturing department and the customer service level.

5.3 Case study scenario one for optimal ordering decision

In this subsection, the proposed PRM framework is illustrated by using it to solve a practical problem of flash memory procurement (Model No: 16Gb 2Gx8 SLC). The case company was incorporated in 1958 in the United States and is headquartered in California. Its business is in the following five segments: manufacturing, testing services, equipment distribution, real estate and fabrication services. It has offices in the United States, Singapore, Malaysia, Thailand and China. The case company designs and produces equipments used in the manufacturing and testing of wafers, devices and other electrical

components. The revenue of the company is about \$35,632,000 in 2013. Flash memory is one of the most commonly used components in semiconductor manufacturing. The following analysis shows how the case company uses the proposed framework to conduct its PRM with both multiple forward contracts and reactive spot market sourcing.

5.3.1 Data for the case study

The procurement department in the case company is responsible for purchasing items that the Singapore branch requests. After interviewing with the procurement officers and conducting the risk identification using SCR-FMEA, it is found that cost, on time delivery, quality and demand are the most important factors considered while choosing suppliers.

Cost is the most important factor. For a manufacturing company, the cost of raw material largely determines the minimum price of their product which they can offer to the market, so the company requires the purchasing department to select suppliers who can provide cheaper raw materials and components. As a procurement officer, his/her bonus is also tied to his/her ability to get more discounts with the supplier. Meanwhile, on time delivery is also a very important factor to be considered. It is common that one product possibly has several hundred components. If one of the components cannot be delivered in time, the whole manufacturing plan would be affected. Moreover, the factor of quality cannot be overlooked either. If raw materials' quality does not reach the required standard, this quality risk would transmit through supply chain and cause greater loss in profit and reputation. Last but not least, the demand of the required flash memory is also quite difficult to be predicted due to the dynamic business environment.

According to the staff in the procurement department, the conventional procedures of procurement in the case company include the following processes: 1) estimating the

demand of this flash memory based on their experience; 2) determining the potential supplier pool by searching their procurement database (IBM Lotus 7.0) with historical transactions of the same or similar items; 3) sending out email to all the suppliers in the pool and request quotations and 4) consolidating the quotations from suppliers, selecting a set of suitable suppliers and allocating orders among them. The problem with this procedure is that all the procurement plans are formulated solely based on the buyer's personal judgment, which is inherently subjective and not accurate enough. Besides, the unmet extra demand reduces the potential profits and affects the key performance indicator of the procurement department. Keeping the additional items as inventory for a long time also brings other risks; the fast pace of the high-tech industry might cause the values of inventories to depreciate dramatically if they are substituted by new technology inventions.

In order to support the case company to mitigate the risk of supply, the proposed PRM framework in Chapter 4 is used. The changes for the existing procurement procedures are mainly in three aspects: using the supplier assessment model to update supplier pool and eliminate those suppliers whose performances are worse than others, adopting the goal programming model to support the decision on allocating the order proportions among selected suppliers and utilizing of spot market to buy extra demand or sell inventories.

After sending out the requests of quotation emails to the supplier pool at the beginning of the procurement period, five suppliers replied and offered their price. The statistics of the five suppliers' uncertain yield based on their past performance are recorded in the database. For the value increment in manufacturing company, the component's value is added to it after it is used in the final product. Same as Haksöz and Kadam (2009), we

assume that the value of each unit is increased to a final value r in the final product. The correlation coefficient can be computed by Monte Carlo simulation using the historical data. Table 5.2 is the summary of the case company data.

Table 5.2: Data of the case company

Date and parameters				
Final Value per	$r=30$	Risk aversion parameter	$k=0.005$	
		Trials per simulation	100,000	
Potential supplier pool				
The supplier No.	Wholesale price w_i	Yield mean μ_y	Yield SD σ_y	
The supplier A	8.5	0.65	0.05	
The supplier B	9.0	0.70	0.05	
The supplier C	9.5	0.75	0.05	
The supplier D	10.0	0.80	0.05	
The supplier E	10.5	0.85	0.05	
Demand and spot price in 12 periods				
Period No.	Demand mean μ_d	Demand SD σ_d	Spot price mean μ_s	Spot price SD σ_s
1	110	26	11.5	2.0
2	100	25	12.0	2.5
3	115	20	12.5	2.5
4	125	24	13.0	2.8
5	120	23	13.5	2.4
6	126	34	15.0	2.5
7	140	29	15.5	3.5
8	139	41	16.0	2.3
9	142	39	15.6	2.4
10	140	35	15.2	2.6
11	136	36	14.8	2.3
12	130	25	13.5	2.4
Correlations				
	Yield	Spot price	Demand	
Yield	1.0	-0.1	-0.05	
Spot price	-0.1	1.0	0.2	
Demand	-0.05	0.2	1.0	
Business Policies				
Estimated fixed cost of adding one more supplier $FC=50$;				
Prohibitions: 1. Place 60% of total orders on a single supplier; 2. Place less than 10% of total orders on a single supplier.				

5.3.2 Optimization model for the case study

According to the situation of the case company, the buyer plans to buy Q units of product with price w to meet demand from end user. The procurement of the case company is exposed to the uncertain demand d and yield y . In order to help the case company to meet the unexpected demand or sell extra stock, spot market is suggested to be used as a reactive source with selling price s per unit. Before designing the optimal procurement plan, the performances of each of the supplier from the supplier pool should be quantified so as to select the optimal portfolio of suppliers. Therefore, if Q units of order are placed on a certain supplier from the supplier pool, yQ units are delivered on time by the supplier because of the uncertain yield y . The additional $(yQ - d)^+$ flash memories are sold to spot market with the profit $(s - w)$ per unit if $s > w$ (or the loss $w - s$ per unit if $s < w$), and the unexpected demand $(d - yQ)^+$ is met via spot market with price s per unit. The fixed cost of doing business with a supplier is FC . Therefore, the assessment model of a potential supplier's profit can be expressed as:

$$\Pi_{buyer} = f_i(R_1, R_2, \dots, R_m; C_1, C_2, \dots, C_n).$$

It consists of the following components:

- 1) the value added from meeting demand of end user;
- 2) minus the procurement cost associated with the order from contract supplier;
- 3) plus the net benefit from selling the excess stock to the spot market, which is positive when the spot price is higher than the wholesale price, and negative when the spot price is lower than the wholesale price;

- 4) plus the net benefit from meeting demand via the spot market, which positive when the final value is higher than the spot price, and negative when the final value is lower than the spot price; and
- 5) minus fixed cost of doing business with the supplier.

Therefore:

$$\Pi_{buyer} = rmin[d, yQ] - wyQ + (s - w)(yQ - d)^+ + (r - s)(d - yQ)^+ - FC.$$

After conducting the risk assessment using the above supplier assessment model, the goal programming for supplier diversification in Subsection 4.4.1 and contract-spot allocation model in Subsection 4.4.2 are used to obtain the optimal ordering plan.

5.3.3 Result analysis

The supplier risk assessment model is implemented and simulated according to the simulation algorithm A-EPSaR proposed in Subsection 4.3.1. The expected profit and SaR are calculated, the results are shown in Table 5.3. Based on these performances, those less favorable suppliers can be eliminated from the potential supplier pool. For example, as it can be seen from Table 5.3, the buyer can obtain a normalized expected profit of 0.0 and normalized SaR 0.66249 on choosing supplier A. This however, is obviously worse comparing with choosing supplier C (normalized expected profit 0.52348 and normalized SaR 0.0). As a result, supplier A should be removed from the supplier's pool. By doing the same way, supplier B is also removed from the supplier's pool because it is less favorable comparing with supplier C.

Table 5.3: The simulation result of the Profit-SaR map

Supplier No.	Expected profit	SaR(95%)	Normalized EP	Normalized SaR
Supplier A	597.01	243.95	0.00000	0.66249
Supplier B	709.00	144.05	0.24213	0.32085
Supplier C	839.13	50.23	0.52348	0.00000
Supplier D	954.03	181.12	0.77190	0.44762
Supplier E	1059.53	342.64	1.00000	1.00000

The normalization function used is: $\frac{x-Min}{Max-Min}$.

With the help of our designed algorithm, all similar less favorable suppliers are weeded out from the pool and an optimal supplier set is determined. A decision support system which integrates all the risk management steps of PRM framework is implemented and it is shown in Figure 5.3. This system can help to assess suppliers based on the expected profit and SaR.

The goal programming model in the decision support system then helps us to determine the proportions of order allocation for each of the suppliers. This enables us to further obtain the optimal number of items to source from contract supplier via inputting the portfolio yield and average wholesale price of the portfolio and use the result of contract-spot allocation model in Chapter 3. From Figure 5.3, we can observe that both suppliers A and B are sifted out from the pool. Suppliers C, D and E are selected to purchase the products from.

Demand and Market Information

Period No.	Demand Mean	Demand SD	Spot Price Mean	Spot Price SD
1	110	15	11.5	2.0
2	100	25	12.0	2.5
3	115	20	12.5	2.5
4	125	16	13.0	2.8
5	120	18	13.5	2.4
6	130	19	15.0	2.5
7	145	15	15.5	3.5
8	150	14	16.0	2.3
9	142	19	15.6	2.4
10	140	13	15.2	2.6

Correlations

	Yield	Spot Price	Demand
Yield	1.0	-0.1	-0.05
Spot Price	-0.1	1.0	0.2
Demand	-0.05	0.2	1.0

Buttons: Edit demand information, Edit spot price, Update correlations

Step1 : Input the data of demand and spot price

Identify Potential Suppliers

Supplier No	Wholesale Price	Yield Mean	Yield Standard Deviation
A	8.5	0.65	0.05
B	9.0	0.70	0.05
C	9.5	0.75	0.05
D	10.0	0.80	0.05
E	10.5	0.85	0.05
*			

Buttons: Add supplier, Update supplier, Delete supplier

Step 2: Input of the suppliers' information

Figure 5.3: The decision support system in the case study

The final procurement plan is shown in Table 5.4. Within the five potential suppliers, supplier A is the avoided supplier with high risk and low expected profit if chosen by the buyer. Supplier B is approved but its performance is worse comparing with supplier C, so it is also eliminated from the pool. The buyer allocates the order among suppliers C, D and E from period 1 to 12. Within the selected supplier pool, the preferred type of supplier C obtains the largest portion of order with a total of 1470 units during the 12 periods, preferred supplier D wins 735 units order at the medium level and the approved type supplier E wins the least with 246 units.

The responsibilities of a purchasing department in a manufacturing company are not only to maximize the profit as large as possible; at the same time it should try its best to

meet the end user's requirements and needs. Figure 5.4 is plotted to show how the proposed PRM framework can help to meet demand at a low risk. As demand is assumed to be normal distribution, high demand is picked to be (demand mean + $3.290527 \times$ demand standard deviation); low demand is (demand mean - $3.290527 \times$ demand standard deviation). The range between high and low demand value is selected to ensure that the possibility that the uncertain demand is within the picked range is 0.999. Therefore, we can confidently say that the situation when demand is not contained in the selected range is quite rare.

Table 5.4: Optimal order allocation among the supplier pool

	Supplier A	Supplier B	Supplier C	Supplier D	Supplier E	Total quantity
Supplier level	Avoided	Approved	Preferred	Preferred	Approved	
1 st period	0	0	82	41	14	137
2 nd period	0	0	78	39	13	130
3 rd period	0	0	102	51	17	170
4 th period	0	0	107	53	18	178
5 th period	0	0	119	60	20	199
6 th period	0	0	132	66	22	220
7 th period	0	0	127	63	21	211
8 th period	0	0	161	80	27	268
9 th period	0	0	153	76	26	255
10 th period	0	0	141	71	23	235
11 th period	0	0	143	72	24	239
12 th period	0	0	125	63	21	209
Total quantity	0	0	1470	735	246	2451
Portfolio yield mean: 0.77; Portfolio yield standard deviation: 0.05; Portfolio average wholesale price: 9.75;						

From period 1 to period 12, the buyer purchases the flash memory chips according to the formulated plan. After comparing the ordered quantity with the high demand, it is found out that high demand and our optimal order quantity are quite close and their average difference is only about 9.54%. This shows the purchasing department can meet the end user's demand in a highly reliable manner. Moreover, the gap between the ordered quantity and the actual demand is purchased through spot market. With the help of spot market and the proposed PRM framework, supply risks are controlled and minimized.

It is obvious that a purchasing department wants to purchase more items from the low cost contract supplier in advance to better meet end user's demand on the premise that the supply risk is controlled. However, without the decision support system, it is often the case that the amount of average order quantity is purchased. Even though the lead time from spot market is negligible, the price is quite high comparing with the long term contract supplier. The buyer cannot meet the end user's demand with a high service level, because the gap between the high demand and average demand is as high as 43.41%.

With the help from the proposed system, purchaser can order the suggested quantity from the contract supplier so as to maximize the revenue by considering yield risk. The detailed comparisons between ordering average quantity and optimal quantity are shown in Figure 5.5. The results show that the buyer can obtain a higher expected profit and a larger objective value after countering the effect of its risk aversion attitude. The value of the objective function is determined from the findings in Chapter 3, which is used to show the combinatorial effects of both expected profit and profit standard deviation. And the larger the objective value is the better. For example, during the first period, the buyer can obtain a higher profit for buying the optimal quantity instead of buying the average

quantity. Even though the profit standard deviation is slightly higher when buying the optimal quantity, the objective value is still much higher for buying the optimal quantity.

5.4 Case study scenario two for delivery arrangement

After conducting the SCR-FMEA risk assessment analysis, the management team considers whether delivery should be managed by itself and the whole process should be monitored, or outsourced and left to suppliers. The process to deliver supplies from supplier to manufacturing factory may be outsourced to the supplier, as suppliers can consolidate the shipment with other company's orders and charges less. But the problem with delivery controlled by suppliers is that they may focus more on cost reduction rather than ensuring the delivery lead time. If the purchasing department is responsible for the arrangement delivery, staffs can find more reliable delivery option and closely monitor the delivery status. Therefore the cost is usually higher if managed by the purchasing team. The management team needs to obtain the risk assessment results for both options and makes delivery arrangement decisions based on them.

Figure 5.4: High-low-average demand and the ordered quantity from selected suppliers

Figure 5.5: Comparisons between ordering average quantity and optimal quantity

5.4.1 Data for the case study

A set of parameters related to delivery lead time and cost breakdown information are obtained from the purchasing department in the case company. The breakdown of costs/lead time into elemental components is useful in finding out the estimations of most likely cost/lead time in the simulation model. In this case scenario, the whole procurement process is broken down into five stages: 1) ordering processing; 2) order acknowledgement; 3) production of supplies; 4) delivery and 5) quality check. In addition, the lead time of delivery is assumed here as normal distribution and this assumption can be relaxed based on the actual need. The whole stages of delivery are studied for the lead time analysis, including:

1. L_{OP} : Average Order Processing (OP) Time
2. L_{OA} : Average Order Acknowledgement (OA) Time
3. L_{POS} : Average Time for Production of Supplies (POS)
4. L_{DC} : Average Delivery Time (DC)
5. L_{QC} : Average Quality Check Time (QC).

In addition, we breakdown cost into three components and it is necessary to mention that the total cost in this case study considers the administrative costs and delivery cost, while the cost of purchased items is not included. The three cost components include the followings:

1. C_{OP} : Cost during electronic Order Processing (OP)
2. C_{OA} : Cost during Order Acknowledgement (OA)
3. C_{DC} : Cost during Delivery (DC)

The delivery of the three selected suppliers C, D and E are studied in this subsection. In this case study, the buyer from a Singapore manufacturing department wants to purchase the semiconductor components from China, from where the components cost is quite low. For instance, suppliers C, D and E are all from China. Suppliers C and D have very few customers in Singapore. If the buyer asks the supplier C or D to take charge of the delivery, the supplier C or D may wait for a long time to consolidate the orders from all customers in Singapore. It will increase the lead time but the cost may be lower. However, since the supplier E has a lot of customers in Singapore, it will take supplier E a shorter time to wait and consolidate orders to deliver to Singapore. Table 5.5 and Table 5.6 show the collected data of lead time and cost respectively from the case company. For the ease of comparison, all the costs and lead time information is gathered by assuming that the amount of items to be delivered from selected suppliers are the same. The subscript “After OS” denotes that the delivery is outsourced to supplier, while “Before OS” means that delivery is kept in house and the purchasing department itself is responsible for the delivery.

5.4.2 Simulation model for the case study

Risk management needs both quantitative and qualitative approaches to identify and assess the potential risks. With respect to qualitative approach, the proposed SCR-FMEA analyzes the impact, occurrence probability and detection rate of potential risks. Applying the procedures of SCR-FMEA, the risks scores and RPN values are used to plot risk scores Pareto chart and RPN Pareto bar chart. Those events with high risk score may not have high RPN as detection is one of the factors affecting RPN.

Table 5.5: Input summary for lead time information

Name	Distribution	Mean	Standard Deviation	25 th Percentile	50 th Percentile	75 th Percentile
The delivery of supplies from forward contract supplier C						
$L_{OP, After OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796
$L_{OP, Before OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796
$L_{OA, After OS}$	PsiLogNormal	1	1	0.4033	0.7071	1.2398
$L_{OA, Before OS}$	PsiLogNormal	1	1	0.4033	0.7071	1.2398
$L_{POS, After OS}$	PsiNormal	10.5	3	8.4765	10.5000	12.5234
$L_{POS, Before OS}$	PsiNormal	8	2	6.6510	8.0000	9.3490
$L_{DC, After OS}$	PsiNormal	9	2	7.6510	9.0000	10.3490
$L_{DC, Before OS}$	PsiNormal	8	1.5	6.9883	8.0000	9.0117
$L_{QC, After OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796
$L_{QC, Before OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796
The delivery of supplies from forward contract supplier D						
$L_{OP, After OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796
$L_{OP, Before OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796
$L_{OA, After OS}$	PsiLogNormal	1	1	0.4033	0.7071	1.2398
$L_{OA, Before OS}$	PsiLogNormal	1	1	0.4033	0.7071	1.2398
$L_{POS, After OS}$	PsiNormal	10	2.5	8.3138	10.0000	11.6862
$L_{POS, Before OS}$	PsiNormal	7	2	5.6510	7.0000	8.3490
$L_{DC, After OS}$	PsiNormal	15	3	12.9765	15.0000	17.0235
$L_{DC, Before OS}$	PsiNormal	12	2	10.6510	12.0000	13.3490
$L_{QC, After OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796
$L_{QC, Before OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796
The delivery of supplies from forward contract supplier E						
$L_{OP, After OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796
$L_{OP, Before OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796
$L_{OA, After OS}$	PsiLogNormal	1	1	0.4033	0.7071	1.2398
$L_{OA, Before OS}$	PsiLogNormal	1	1	0.4033	0.7071	1.2398
$L_{POS, After OS}$	PsiNormal	11	2.5	9.3138	11.0000	12.6862
$L_{POS, Before OS}$	PsiNormal	10	2	8.6510	10.0000	11.3490
$L_{DC, After OS}$	PsiNormal	13	2	11.6510	13.0000	14.3490
$L_{DC, Before OS}$	PsiNormal	14	1	13.3255	14.0000	14.6745
$L_{QC, After OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796
$L_{QC, Before OS}$	PsiLogNormal	2	2	0.8066	1.4142	2.4796

Table 5.6: Input summary for cost information

Name	Distribution	Mean	Standard Deviation	25 th Percentile	50 th Percentile	75 th Percentile
The delivery of supplies from forward contract supplier C						
C_{DC} , Before OS	PsiNormal	159619.4	100	159551.95	159619.40	159686.85
C_{DC} , After OS	PsiNormal	135875.2	155	135770.65	135875.20	135979.74
C_{OP} , Before OS	PsiNormal	250	60	209.53	250.00	290.46
C_{OP} , After OS	PsiNormal	200	50	166.27	200.00	233.72
C_{OA} , Before OS	PsiNormal	150	40	123.02	150.00	176.97
C_{OA} , After OS	PsiNormal	150	40	123.02	150.00	176.97
The delivery of supplies from forward contract supplier D						
C_{DC} , Before OS	PsiNormal	200507.3	134	200416.91	200507.30	200597.68
C_{DC} , After OS	PsiNormal	178960.3	157	178854.40	178960.3	179066.19
C_{OP} , Before OS	PsiNormal	250	60	209.53	250.00	290.46
C_{OP} , After OS	PsiNormal	200	50	166.27	200.00	233.72
C_{OA} , Before OS	PsiNormal	150	40	123.02	150.00	176.97
C_{OA} , After OS	PsiNormal	150	40	123.02	150.00	176.97
The delivery of supplies from forward contract supplier E						
C_{DC} , Before OS	PsiNormal	198570.2	124	198486.56	198570.2	198653.83
C_{DC} , After OS	PsiNormal	168960.5	132	168871.46	168960.5	169049.53
C_{OP} , Before OS	PsiNormal	250	60	209.53	250.00	290.46
C_{OP} , After OS	PsiNormal	200	50	166.27	200.00	233.72
C_{OA} , Before OS	PsiNormal	150	40	123.02	150.00	176.97
C_{OA} , After OS	PsiNormal	150	40	123.02	150.00	176.97

Two measures including the total average lead time and total costs in supply chain are used. Two simplified mathematical representations are used to quantify lead time uncertainty associated with outsourcing decision making. Total Lead time is a function of time components shown in the following expression.

$$\text{Total Estimated Lead Time} = f(L_{OP}, L_{OA}, L_{POS}, L_{DC}, L_{QC})$$

Hence, the total estimated lead time output field of the simulation spreadsheet can be expressed as a summation of all lead time at different points in the supply chain given by:

$$\text{Total Estimated Lead Time} = f(L_{OP} + L_{OA} + L_{POS} + L_{DC} + L_{QC}).$$

Similarly, Total Cost in supply chain is a function of cost components, shown in the following expression.

$$\text{Total Estimated Cost} = f(C_{OP}, C_{OA}, C_{DC}).$$

Therefore, the total estimated cost output field of the simulation spreadsheet can be expressed as a summation of all estimated cost at different points in the procurement given by:

$$\text{Total Estimated Cost} = f(C_{OP} + C_{OA} + C_{DC}).$$

Therefore, the total estimated cost savings output field can be expressed as a summation of the difference of cost before and after outsourcing with respect to before outsourcing risk shown as follows:

Total Estimated Supply Chain Cost Savings =

$$\frac{f(C_{OP} + C_{OA} + C_{DC}) \text{ After}_{OS} - f(C_{OP} + C_{OA} + C_{DC}) \text{ Before}_{OS}}{f(C_{OP} + C_{OA} + C_{DC}) \text{ Before}_{OS}}.$$

Figure 5.6: Simulation of risk assessment for case study

The collected data can be assigned to the individual risk factor of the spreadsheet model in the Subsection 5.4.2. For example, $L_{OP, \text{Before OS}}$ is highlighted in Figure 5.6 to explain how the Psi function is used for parameter setting. After all the values are set in the model, Monte Carlo simulation can be performed and outputs are obtained.

5.4.3 Result analysis

After collecting information related to cost/lead time and conducting the simulation, we are able to know whether outsourcing is reasonable or not based on the simulation results (shown in Figure 5.7). To provide a detailed analysis, the variations of lead time and cost are examined for before outsourcing and after outsourcing scenarios. A total cost saving analysis is conducted in Subsection 5.4.3.3.

Figure 5.7: Monte Carlo simulation results for before and after outsourcing

5.4.3.1 Total average lead time results

Risk Solver's Monte Carlo simulation allows user to get the distribution result of total cost and customer lead time based on 1000 trials. The output for total average customer lead time result is shown in Figure 5.7. Each possible outcome is obtained by 1000 trials. The result placed side by side helps to contrast frequencies distributions of before and after outsourcing of lead time and supply chain cost, respectively.

The outcome can be generated from the probabilistic inputs shown in Table 5.5 which provides summary information of the different components of lead time used in the simulation. In Table 5.7, the total lead time for supplier C before outsourcing with the average of 21.00 days is lower than after outsourcing (24.53 days). This implies that a newly implemented delivery outsourcing arrangement increases the average lead time. A shorter lead time achieved by controlling and monitoring the delivery by itself can possibly increase the supply reliability. For the case of supplier D, there is an even larger

difference of the lead time between before and after outsourcing. But for supplier E, the lead time does not have a large difference. In fact, apart from the differences of lead time, related cost information should also be considered so as to determine whether the delivery should be outsourced to supplier or not.

Table 5.7: Output summary of uncertain lead time

Name	Mean	Standard Deviation	25 th Percentile	50 th Percentile	75 th Percentile
The delivery of supplies from forward contract supplier C					
Total _{After OS}	24.5307	4.8192	21.3189	24.4655	27.3289
Total _{Before OS}	21.0029	3.9357	18.3069	20.7075	23.1729
The delivery of supplies from forward contract supplier D					
Total _{After OS}	30.0060	5.1278	26.3992	29.7274	33.1233
Total _{Before OS}	24.0168	4.2185	21.0361	23.8454	26.2193
The delivery of supplies from forward contract supplier E					
Total _{After OS}	29.0009	4.2117	26.0304	28.5839	31.4463
Total _{Before OS}	28.9894	3.6645	26.5470	28.6789	30.9766

5.4.3.2 Total average cost results

The result of total average cost shown in Table 5.8 is generated by the probabilistic inputs distributions from the data in Table 5.6. Table 5.6 provides the summarized information of the different cost components. From the result of supplier C, the mean of total average cost before outsourcing is S\$160019.49 and it is reduced to S\$136225.18 after outsourcing to the supplier. The cost after outsourcing is about 85% of the original cost before outsourcing. This leads us to conclude that there is substantial cost savings and it is benefited from the outsourcing arrangement. According to the lead time results from Subsection 5.4.3.1, the total lead time increases about 3 days after outsourcing. The purchasing department team can make the decision to see whether it is worthy to spend

three more days by outsourcing and save about 15% costs. If the delivery of supplier D is outsourced, the cost can be saved for 10% but the lead time is about 6 days longer. If supplier E's delivery is outsourced, cost can be reduced by 15% and the lead time is almost unchanged. So in this situation, supplies from E can be outsourced to supplier E.

Table 5.8: Output summary of uncertain cost

Name	Mean	Standard Deviation	25 th Percentile	50 th Percentile	75 th Percentile
The delivery of supplies from forward contract supplier C					
$C_{Total, Before OS}$	160019.49	115.86	159945.45	160017.46	160097.99
$C_{Total, After OS}$	136225.18	169.37	136116.38	136224.70	136342.03
The delivery of supplies from forward contract supplier D					
$C_{Total, Before OS}$	200907.26	147.01	200804.53	200910.88	201013.61
$C_{Total, After OS}$	179310.25	167.66	179199.53	179307.73	179423.77
The delivery of supplies from forward contract supplier E					
$C_{Total, Before OS}$	198970.17	141.97	198872.35	198969.69	199063.58
$C_{Total, After OS}$	169310.44	147.87	169212.05	169312.99	169408.87

By adopting this outsourcing decision support methodology, firms can improve their supply chain stability while reducing cost at the same time. This methodology has several implications for practitioners, especially for logistics management consultants, professionals from logistics decision support department:

- The qualitative method is suitable in capturing the impact of risk in the supply chain. The SCR-FMEA method can be regarded as a qualitative risk assessment technique. It can be used to identify the most critical risk. This qualitative method

allows practitioners to plan ahead and mitigate vulnerabilities. The qualitative SCR-FMEA risk management technique should be done at the planning stage.

- The quantitative risk assessment is conducted with the support of simulation software. The key performance indicators are used to evaluate the performance of outsourcing certain logistics functions. It is necessary to understand that different firms may have different performance indicators, so the measures of performance should be revised accordingly. For instance, two parameters L_{Total} and C_{Total} are used as the key indicator for delivery outsourcing risks in our case study. Lead Time and cost simulations are done for two scenarios (i.e. before and after outsourcing). It will aid the company to make decision on logistics outsourcing. The input variables that involve risks are all described through distributions. Although it is difficult to estimate precisely the distribution of parameters in the model, simulation tool provides a rich palette of distribution and fitting test to reflect expected performances. The spreadsheet simulation makes it easier to include desired assumptions. Also, simulation provides the ability to measure different outcome variable such as cost saving which determines the profitability of outsourcing.
- The methodology can identify risks and evaluate performance for both before and after outsourcing scenarios. It will help logistics management consultants to figure out professional solutions to clients, or aid logistics decision support department to submit high quality report to managers.

The proposed outsourcing methodology is practical and easy-to-use. Sensitivity analysis can be done to show which logistics process affects the performance indicators

the most. This kind of information should be shared with service providers, so that they can better meet the firm's need and this is good for the formation of cooperative outsourcing partnership.

This methodology also requires practitioners to have a solid understanding of all the possible risks related to logistics. Therefore, it is recommended to adopt different qualitative techniques such as focus group and Delphi to find out more about hidden risk of outsourcing. To conclude, both qualitative and quantitative risk assessment techniques should be included to provide the most complete picture.

5.5 Summary

This chapter uses a case study to illustrate how to use the generic PRM framework to assess and mitigate risks in procurement. A case example of purchasing from up to five forward contract suppliers and spot market is analyzed. Optimal order allocations among forward contracts and spot market are obtained. The results are also analyzed and compared for buying optimal number with the average number. For the delivery outsourcing decision making, key performance variables and the risk of delivery outsourcing are analyzed with basic statistical concepts. It provides a generic guideline for practitioners to assess logistics outsourcing, especially for logistics management consultant and professionals for evaluating the risk and impact of outsourcing.

Chapter 6

Conclusions

This chapter summarizes the conclusions, contributions of this thesis as well as the limitations of this research. The possible extensions of this work are proposed to provide directions for further studies.

6.1 Summary of the research

Supply uncertainty is one of the main concerns from buyers' perspective in today's complicated supply chain. Facing the yield risk from suppliers and demand uncertainties from customers, adopting reactive supply via spot market on top of forward contract is a strategic procurement option for manufacturing companies, as delivery lead time from spot market is shorter than forward contract, and the regulation of spot market is very rigorous.

In Chapter 3, closed-form results are provided for determining the optimal order quantity from the contract suppliers when spot market can be used for BS. For other three scenarios (BO, SO and PC), multiple parameterized simulations are carried out using Risk Solver to analyze which procurement decision should be made. In our model, correlations

between uncertainties (correlation between demand and spot price, correlation between yield and spot price and correlation between demand and yield) are also incorporated.

Our model in Chapter 3 provides some managerial insights for buyers. The comparison analysis between considering and ignoring yield risk helps the buyer to understand that yield risk is critical under the following situations: buyer's risk aversion is small; spot market price is high and spot market price variation is large. Under these situations, buyers are strongly recommended to take into account yield risk when designing procurement plans. In addition, the result also shows that the buyer should order the largest possible amount of products in a weakly correlated environment, thus obtaining the largest expected profit when exposed to the same degree of profit variation. The proposed model can help buyers determine optimal order decisions and obtain more profits in the turbulent market.

In Chapter 4, an integrated PRM framework is proposed to support decision making of 1) optimal order allocation among multiple suppliers in the presence of spot market and 2) optimal delivery arrangement. The effects of correlated demand, yield and price uncertainties are also considered in the framework. To our knowledge, there is a lack of complete and quantitative procurement decision support system with the existence of spot market among current research literatures. To address the limitations of the current gap, our proposed framework provides a solution to model multiple intercorrelated procurement risks, with decision support mechanism to utilize multiple contract suppliers and the spot market for procurement risk management.

The decision support system based on the proposed PRM framework is also designed and developed. Under this system, buyers can identify the specific risks in their

procurement and build their own profit model. Supply risk assessment is supported by the Monte Carlo simulation with two comparison indicators: expected profit and SaR. These two unified risk indexes resolve the complexity of multi-dimensions risks assessment. After conducting pair-wise comparisons of performances among potential suppliers, only those who favorable suppliers are still kept in the pool. When assigning orders in the supplier pool, the buyer can adjust the weight of the two objectives (increase profit and mitigate risks) in line with their needs. Once the optimal portfolio with order share is determined, the buyer can figure out the average portfolio yield and wholesale price. The buyer can then obtain the optimal total quantity from contract suppliers, while the rest of uncertain demand can be met through the reactive supply channel (spot market).

Chapter 5 provides a case study to illustrate the application of the proposed methodologies in real-life problems. By adopting the PRM framework, manufacturing companies can improve their supply chain stability and reduce the operational cost at the same time. The performance of proposed decision support system is illustrated by a real case of purchasing flash memory for a semi-conductor manufacturing company. Compared with the conventional way of procurement planning which is merely based on estimation and experience, the proposed PRM framework assists in eliminating less favorable suppliers from the supplier pool and allocating order among the optimal supplier pool. The risk of supply is reduced and a sustainable development of procurement is ensured.

The quantitative risk assessment is conducted with the support of simulation software. Key performance indicators are used to evaluate the performance of outsourcing certain logistics functions. It is necessary to understand that different companies may have

different performance indicators, so the measurement of performance should be set accordingly. For instance, two parameters L_{Total} and C_{Total} are used as the key performance indicators for delivery outsourcing risks in our case study. Lead time and cost simulations are done for two scenarios (i.e. before and after outsourcing). They will aid the company to make decision on logistics outsourcing. The input variables that involve risks are all described through probability distributions. Although it is difficult to estimate precisely the distribution of parameters in the model, simulation tool provides a rich palette of probability distribution and fitting test to reflect expected performances.

The delivery outsourcing methodology can identify risks and evaluate performance for both before and after outsourcing scenarios. This will help logistics management consultants to figure out professional solutions to clients, or support decision makers to make the decision relate to logistics activities outsourcing. The proposed outsourcing decision support methodology is practical and easy to use. The simulation report generated by Risk Solver presents a variety of basic descriptive statistics measures such as mean and standard deviation, and future work can be done by using advanced statistical measures such as skewness, kurtosis etc. These statistics measures may also be used to conduct more in-depth analysis if required. In addition, sensitivity analysis can be done to show which logistics process affects the performance indicators the most. This kind of information should be shared with service providers so that they can further improve the service quality, which is important for the setup of strategic outsourcing partnership. This case study has several implications for practitioners, especially for procurement management consultants and professionals for strategic management of logistics activities outsourcing.

6.2 Contributions of this research study

The contributions of this research are summarized below.

- Designed a novel decision support framework which helps the buyer to make optimal and robust procurement decision including supplier selection and order allocation among multiple supplier sources;
- Proposed an innovative Profit-SaR performance matrix to assist evaluating suppliers and eliminating less favorable suppliers, without the complexity of comparing suppliers with multiple dimension risks ;
- Achieved optimal order allocation decision making among multiple forward contract suppliers via goal programming model, which fulfils the combinatorial objectives of maximized expected profit as well as SaR;
- Conducted an in-depth study on reactive purchase planning via spot market to make optimal procurement decision;
- Effectively addressed the correlations among yield, demand and spot price uncertainties, and closed-form results are derived. This achievement is an extension of Seifert et al. (2004), which assumes no supply risk;
- Proposed an innovative way of modeling pure contract sourcing and limited spot market functions (buying or selling only via spot market) using multiple parameterized Monte Carlo simulations. In particular, this practical modeling method can be easily carried out by industry practitioners and
- Designed a qualitative risk assessment technique, the SCR-FMEA model, to capture the impact of risk in the supply chain management. It can be used to

identify the most critical risk in the process and allows practitioners to plan ahead to mitigate vulnerabilities at the planning stage.

6.3 Limitations and future work

There are some limitations to our work where potential future works can be done.

- ❖ **Limitation 1: The general applicability of our model to purchase all commodities and products.** Currently, not all raw materials and commodities can be purchased from spot markets. Indeed, only a few of them are commonly sourced from spot markets. For example, spot markets are quite common for purchasing memory chips, such as dynamic random access memory and flash memory. One of the popular B2B platforms is DRAMeXchange. Other products available for spot market trading include grains, livestock, steel, oil and chemicals.
- **Future work 1: To generalize our model into the procurement of other commodities.** It may need to consider other reactive channels, such as local supplier or option and futures contracts from the financial markets.
- ❖ **Limitation 2: Our model does not consider the dependencies among unreliable suppliers.** In reality, the performance of suppliers may have correlations. For example, if two suppliers A and B are located in the same city, and if supplier A fails to deliver due to its production delayed by a hurricane, supplier B is highly possible to be affected too. However, the modeling of such correlation is so complex that sometimes it's very hard to obtain analytical results using common mathematical methods.
- **Future work 2: To incorporate correlations between unreliable suppliers using copulas.** During the literature review, Copula function is found to be a useful method to model relationships between distributions. In the future, we will continue to

leverage on Copula function to model the correlations between unreliable suppliers. Moreover, the correlation setting used in this model is Pearson's product-moment coefficient, which is a simple linear correlation. Thus another research direction that can be explored is incorporating a more sophisticated measure to model dependencies between uncertainties.

- ❖ **Limitation 3: Not able to model the impact of inventory for generalized commodity types.** In our study, the impact of inventory is not considered as we focused on components in the high-tech sector, such as memory chips, which quickly depreciate in value with the advancement of technology. Thus buyers are active in both buying and selling memory chips in the spot market rather than keeping inventories in their warehouse. However, this is not always the case for all the commodities. For some kinds of commodities, such as grains oil and steels, their values remain almost unchanged within a relatively long period of time. Thus it is actually preferred to keep inventories so as to prevent production delay due to short of raw materials.
- **Future work 3: To consider inventory in the model for generalized commodity types.** In order to enhance our model to be able to cater more types of commodities, inventory should be considered. Possible research topics may include but not limited to: the impact of inventory cost to the overall profit; the value change during the holding period; damage risk and defective rate in inventory management and possible additional profit from short-term lease of the inventories, such as gold, silver and platinum.

- ❖ **Limitation 4: Not able to consider the capacity limitation and liquidity restriction of the spot market.** In some cases, the spot market may not be able to provide as much supply of items as the buyer requires. More importantly, the spot market may not be liquid enough to provide the commodity instantly. However in our model we actually assumed unlimited capacity and ideal liquidity of the spot market.
- **Future work 4: To take into consideration the capacity limitation and liquidity restriction of the spot market.** When making the procurement decision, the buyer should prepare for the situation that the spot market may not have enough products to meet the demand, or the sellers in the spot market may only be able to deliver the goods in a few days/months. Therefore, the buyer shall adjust the procurement plan from the forward contract suppliers at the first stage, and also source for alternative channels of supply at the same time.

References

Agrawal, N. and S. Nahmias, 1997. Rationalization of the supplier base in the presence of yield uncertainty. *Production and Operations Management* 6(3): 291-308.

Akella, R., V.F. Araman and J. Kleinknecht, 2001. B2B markets: Procurement and supplier risk management in e-business. *Supply Chain Management: Models, Applications, and Research Directions*. Kluwer Academic Publishers: Dordrecht.

Anderson, T.W, 1958. An introduction to multivariate statistical analysis. John Wiley and Sons, New York.

Aouam, T., R. Rardin and J. Abrache, 2010. Robust strategies for natural gas procurement. *European Journal of Operational Research* 205(1): 151-158.

Arnold, J., S. Minner and B. Eidam, 2009. Raw material procurement with fluctuating prices. *International Journal of Production Economics* 121(2): 353-364.

Blake, P., 2000. Chemical e-commerce models emerge. *Chemical Market Reporter*. New York.

Bohrnstedt, G.W. and A.S. Goldberger, 1969. On the exact covariance of products of random variables. *Journal of the American Statistical Association* 64(328): 1439-1442.

Bollapragada, S. and T. Morton, 1999. Myopic heuristics for the random yield problem. *Operations Research* 47(5): 713-722.

Bonser, J. and S. Wu, 2001. Procurement planning to maintain both short-term adaptiveness and long-term perspective. *Management Science* 47(6): 769-786.

- Burke, G., J.E. Carrillo and A.J. Vakharia, 2009. Sourcing decisions with stochastic supplier reliability and stochastic demand. *Production and Operations Management* 18(4): 475-484.
- Burnetas, A. and S. Gilbert, 2001. Future capacity procurements under unknown demand and increasing costs. *Management Science* 47(7): 979-992.
- Buzacott J.A. and H.S. Peng, 2012. Contract design for risk sharing partnerships in manufacturing. *European Journal of Operational Research* 218(3): 656-666.
- Campbell, A.M. and P.C. Jones, 2011. Prepositioning supplies in preparation for disasters. *European Journal of Operational Research* 209(2): 156-165.
- Carbone T.A. and D. D. Tippet, 2004. Project risk management using the project risk FMEA. *Engineering Management Journal* 16(4): 28-36.
- Carrion, M., A.J. Conejo and Arroyo, J. M, 2007. Forward contracting and selling price determination for a retailer. *IEEE Transactions on Power Systems* 22(4): 2105-2114.
- Chambers, M.J. and A. Bailey, 1996. A theory of commodity price fluctuations. *Journal of Political Economy* 104(5): 924-957.
- Chaouch, B., 2007. Inventory control and periodic price discounting campaigns. *Naval Research Logistics* 54(1): 94-108.
- Chauhan, S., A. Dolgui and J.M. Proth, 2009. A continuous model for supply planning of assembly systems with stochastic component procurement times. *International Journal of Production Economics* 120(2): 411-417.
- Chen K.B. and T.J. Xiao, 2011. Ordering policy and coordination of a supply chain with two-period demand uncertainty. *European Journal of Operational Research*. 215(2):347-357.

- Chen, H., J. Chen and Y. Chen, 2006. A coordination mechanism for a supply chain with demand information updating. *International Journal of Production Economics* 103(1): 347-361.
- Chen, J.F., D.D. Yao and S.H. Zheng, 2001. Optimal replenishment and rework with multiple unreliable supply sources. *Operations Research* 49(3): 430-443.
- Chen, S.L. and C.L. Liu, 2007. Procurement strategies in the presence of the spot market and analytical framework. *Production Planning and Control* 18(4): 297-309.
- Cheng, C.B., 2011. Reverse auction with buyer–supplier negotiation using bi-level distributed programming. *European Journal of Operational Research* 211(3): 601-611.
- Choi, S.Y. and A. Ruszczyński, 2011. A multi-product risk-averse newsvendor with exponential utility function. *European Journal of Operational Research* 214(1):78-84.
- Chopra, S. and M.S. Sodhi, 2004. Managing risk to avoid supply chain breakdown. *MIT Sloan Management Review* 46(1): 52-61.
- Costantino, N. and R. Pellegrino, 2010. Choosing between single and multiple sourcing based on supplier default risk: A real options approach. *Journal of Purchasing and Supply Management* 16(1): 27-40.
- Das, S.K. and L. Abdel-Malek, 2003. Modeling the flexibility of order quantities and lead times in supply chains. *International Journal of Production Economics* 85(2): 171-181.
- Ellis, S., R.M. Henry and J. Shockley, 2010. Buyer perceptions of supply disruption risk: A behavioral view and empirical assessment. *Journal of Operations Management* 28(1): 34-46.

- Erdem, A. and S. Özekici, 2002. Inventory models with random yield in a random environment. *International Journal of Production Economics* 78(3): 239-253.
- Erhun, F., P. Keskinocak and S. Tayur, 2008. Dynamic procurement in a capacitated supply chain facing uncertain demand. *IIE Transactions* 40(8): 733-748.
- Evans, J. R., David L.O. 1998. *Introduction to simulation and risk analysis*, Upper Saddle River, NJ., Prentice-Hall.
- Federgruen, A. and N. Yang, 2008. Selecting a portfolio of suppliers under demand and supply risks. *Operations Research* 56(4): 916-936.
- Federgruen, A. and N. Yang, 2009. Optimal supply diversification under general supply risks. *Operations Research* 57(6): 1451-1468.
- Federgruen, A. and N. Yang, 2011. Procurement strategies with unreliable suppliers. *Operations Research* 59(4): 1033-1039.
- Fleischhacker, A.J. and Y. Zhao, 2011. Planning for demand failure: A dynamic lot size model for clinical trial supply chains. *European Journal of Operational Research* 211(3): 496-506.
- Fong, D.K.H., V.M. Gempesaw and J.K. Ord, 2000. Analysis of a dual sourcing inventory model with normal unit demand and erlang mixture lead times. *European Journal of Operational Research* 120(1): 97-107.
- Fotopoulos, S. B., X. Hu and C.L. Munson, 2008. Flexible supply contracts under price uncertainty. *European Journal of Operational Research* 191(1): 253-263.
- Fu, Q., C.Y. Lee and C.P. Teo, 2010. Procurement management using options: Random spot price and the portfolio effect. *IIE Transactions* 42(11): 793-811.

Ghodsypour, S. H. and C. O'Brien, 1998. A decision support system for supplier selection using an integrated analytical hierarchy process and linear programming. *International Journal of Production Economics* 56(1):199-212.

Goel, A. and G. Gutierrez, 2004. Integrating spot and futures commodity market in the optimal procurement policy of an assemble-to-order manufacturer. Working Paper, School of Business, University of Texas, Austin, TX.

Golovachkina, N. and J. Bradley, 2002. Supplier-manufacturer relationships under forced compliance contracts. Working Paper, Management Department, University of Texas, Austin.

Gosling, J., L. Purvis and M.M. Naim, 2010, Supply chain flexibility as a determinant of supplier selection. *International Journal of Production Economics* 128(1): 11-21.

Grasman, S., Z. Sari and T. Sari, 2007. Newsvendor solutions with general random yield distributions. *Operations Research* 41(4): 455-464.

Guo, Z., F. Fang and A.B. Whinston, 2006. Supply chain information sharing in a macro prediction market. *Decision Support Systems* 42(3):1944-1958.

Gurnani, C., 1984. Capital budgeting: theory and practice. *The Engineering Economist* 30(1): 19-46.

Gurnani, H., R. Akella and J. Lehoczky, 2000. Supply management in assembly systems with random yield and random demand. *IIE Transactions* 32(8): 701-714.

Haksöz, Ç. and S. Seshadri, 2006. A supply chain contract in the presence of spot market trading and hedging. Working Paper, Cass Business School, London, UK.

Haksöz, Ç. and S. Seshadri, 2007. Supply chain operations in the presence of a spot market: A review with discussion. *Journal of the Operational Research Society* 58(11): 1412-1429.

Haksöz, Ç. and A. Kadam, 2009. Supply portfolio risk. *The Journal of Operational Risk* 4(1): 59-77.

Haksöz, Ç., C. Kadam and T. Orhanl, 2008. Supply risk in fragile contracts. *MIT Sloan Management Review* 49(2): 6-8.

Hariga, M. and M. Ben-Daya, 1999. Some stochastic inventory models with deterministic variable lead time. *European Journal of Operational Research* 113(1): 42-51.

Hazra, J. and B. Mahadevan, 2009. A procurement model using capacity reservation. *European Journal of Operational Research* 193(1): 303-316.

Hätönen, J. and T. Eriksson, 2009. 30+ years of research and practice of outsourcing – exploring the past and anticipating the future. *Journal of International Management* 15(2): 142-155.

Hsu, P., H. Teng, and H.M. Wee, 2009. Optimal lot sizing for deteriorating items with triangle-shaped demand and uncertain lead time. *European Journal of Industrial Engineering* 3(3): 247-260.

Hsu, P., H.M. Wee and H. Teng, 2007. Optimal ordering decision for deteriorating items with expiration date and uncertain lead time. *Computers and Industrial Engineering* 52(4): 448-458.

Inderfurth, K. and P. Kelle, 2011. Capacity reservation under spot market price uncertainty. *International Journal of Production Economics* 133(1): 272-279.

Kawai, M., 1983. Spot and futures prices of nonstorable commodities under rational expectations. *The Quarterly Journal of Economics* 98(2): 235-254.

Kelle, P., S. Transchel and S. Minner, 2009. Buyer-supplier cooperation and negotiation support with random yield consideration. *International Journal of Production Economics* 118(1): 152-159.

Keren, B., 2009. The single-period inventory problem: Extension to random yield from the perspective of the supply chain. *Omega* 37(4): 801-810.

Keskin, B. B., S. H. Melouk and I.L. Meyer, 2010. A simulation-optimization approach for integrated sourcing and inventory decisions. *Computers and Operations Research* 37(9): 1648-1661.

Kim, M. and C. Jim, 2011. Japan quake tests supply chain from chips to ships. <http://www.reuters.com/article/2011/03/14/us-japan-quake-supplychain-idUSTRE72D1FQ20110314>. Accessed on 16Feb2014.

Kouvelis, P. and J. Li, 2008. Flexible backup supply and the management of lead time uncertainty. *Production and Operations Management* 17(2): 184-199.

Kraljic, P., 1983, Purchasing must become supply management. *Harvard Business Review* 61(5):109-117.

Kull, T. and S. Talluri, 2008. A supply risk reduction model using integrated multicriteria decision making. *IEEE Transactions on Engineering Management* 55(3): 409-419.

Levary, R. R., 2007. Ranking foreign suppliers based on supply risk. *Supply Chain Management: An International Journal* 12(6): 392-394.

- Li, C. and P. Kouvelis, 1999. Flexible and risk-sharing supply contracts under price uncertainty. *Management Science* 45(10): 1378-1398.
- Li, S. and L. Wang, 2010. Outsourcing and capacity planning in an uncertain global environment. *European Journal of Operational Research* 207(1): 131-141.
- Li, S., A. Murat and W. Huang, 2009. Selection of contract suppliers under price and demand uncertainty in a dynamic market. *European Journal of Operational Research* 198(3): 830-847.
- Li X., Y.J. Li and X.Q. Cai, 2011. On a multi-period supply chain system with supplementary order opportunity. *European Journal of Operational Research* 209(3): 273-284.
- Li Y. and S. Gupta, 2011. Strategic capability investments and competition for supply contracts. *European Journal of Operational Research* 214(2): 273-283.
- Li Y.M. and J.H. Li, 2011. Analyzing online B2B exchange markets: Asymmetric cost and incomplete information. *European Journal of Operational Research* 214(3): 722-731.
- Lin J. and T.S. Ng, 2011. Robust multi-market newsvendor models with interval demand data. *European Journal of Operational Research* 212(2): 361-373.
- Lin, L. and K. Hou, 2005. An inventory system with investment to reduce yield variability and set-up cost. *Journal of the Operational Research Society* 56(1): 67-74.
- Lysons, K. and B. Farrington, 2006. *Purchasing and supply chain management*, FT Press.
- Maddah, B., M.K. Salameh and G.M. Karame, 2009. Lot sizing with random yield and different qualities. *Applied Mathematical Modelling* 33(4): 1997-2009.
- Markowitz, H., 1952. Portfolio selection. *Journal of Finance* 7(1): 77-91.

Martel, A., M. Diaby and F. Boctor, 1995. Multiple items procurement under stochastic nonstationary demands. *European Journal of Operational Research* 87(1): 74-92.

McKinsey & Company and CAPS Research, 2000. Coming into focus: Using the lens of economic value to clarify the impact of B2B marketplaces. White Paper, McKinsey & Company, New York.

Mendelson, H. and T.I. Tunca, 2007. Strategic spot trading in supply chains. *Management Science* 53(5): 742-759.

Mukhopadhyay, S.K. and H. Ma, 2009. Joint procurement and production decisions in remanufacturing under quality and demand uncertainty. *International Journal of Production Economics* 120(1): 5-17.

Nagali, V., J. Hwang, D. Sanghera, M. Gaskins, M. Pridgen, T. Thurston, P. Mackenroth, D. Branvold, P. Scholler and G. Shoemaker, 2008. Procurement risk management (PRM) at Hewlett-Packard company. *Interfaces* 38(1): 51-60.

Nagar, L. and K. Jain, 2008. Supply chain planning using multi-stage stochastic programming. *Supply Chain Management: An International Journal* 13(3): 251-256.

Ngwenyama, O.K. and N.E. Bryson, 1999. Making the information systems outsourcing decision: A transaction cost approach to analyzing outsourcing decision problems. *European Journal of Operational Research* 115(2): 351-367.

Pineda, S., A. J. Conejo and M. Carrion, 2008. Impact of unit failure on forward contracting. *IEEE Transactions on Power Systems* 23(4): 1768-1775.

Porter, M.E, 1991. Strategy: seeking and securing competitive advantage in how competitive forces shape strategy. Cambridge, MA: Harvard Business Review: 11-26.

- Qiu, L.F, H.X Rui, and A.B. Whinston, 2011. A Twitter-Based Prediction Market: Social Network Approach. ICIS 2011 Proceedings.
- Rocha, P. and D. Kuhn, 2012. Multistage stochastic portfolio optimization in deregulated electricity markets using linear decision rules. *European Journal of Operational Research* 216(2): 397-408.
- Rodd, Z., 2013. Thailand floods disrupt supply chains. <https://www.businessinsurance.com/article/99999999/NEWS060101/399999816>. Accessed on 16Feb2014.
- Routledge, B.R., D.J. Seppi and C.S. Spatt, 2000. Equilibrium forward curves for commodities. *Journal of Finance* 55(3): 1294-1388.
- Ruiz-Torres, A.J. and F. Mahmoodi, 2007. The optimal number of suppliers considering the costs of individual supplier failures. *Omega* 35(1): 104-115.
- Seifert, R. and K. Langenberg, 2011. Managing business dynamics with adaptive supply chain portfolios. *European Journal of Operational Research* 215(3): 551-562.
- Seifert, R., U. Thonemann and W. Hausman, 2004. Optimal procurement strategies for online spot markets. *European Journal of Operational Research* 152(3): 781-799.
- Siripatanakulhajorn, S.Y. Saisho and Y. Fujii, 2006. Study on stochastic optimal electric power procurement strategies with uncertain market prices. *Electrical Engineering in Japan* 156(2): 32-42.
- Sodhi, M.S. and C.S. Tang, 2009. Managing supply chain disruptions via time-based risk management. *Managing Supply Chain Risk and Vulnerability, Tools and Methods for Supply Chain Decision Makers*, Springer, London, 29-42.
- Spinler, S. and A. Huchzermeier, 2006. The valuation of options on capacity with cost and demand uncertainty. *European Journal of Operational Research* 171(3): 915-934.

- Spinler, S., A. Huchzermeier and P. Kleindorfer, 2003. Risk hedging via options contracts for physical delivery. *OR Spectrum* 25(3): 379-395.
- Sting, F. J. and A. Huchzermeier, 2010. Ensuring responsive capacity: How to contract with back up suppliers. *European Journal of Operational Research* 207(2): 725-735.
- Stoll, H.R. and R.E. Whaley, 1993. *Futures and Options: Theory and Applications*. South-Western Publishing Co., Cincinnati, OH.
- Sun, G.J., Y.K. Liu and Y.F. Lan, 2010. Optimizing material procurement planning problem by two-stage fuzzy programming. *Computers and Industrial Engineering* 58(1): 97-107.
- Swaminathan, J. and J. Shanthikumar, 1999. Supplier diversification: Effect of discrete demand. *Operations Research Letters* 24(5): 213-221.
- Talluri, S., R. Narasimhan and W.M. Chung, 2010. Manufacturer cooperation in supplier development under risk. *European Journal of Operational Research* 207(1): 165-173.
- Tang, C., 2006. Perspectives in supply chain risk management. *International Journal of Production Economics* 103(2): 451-488.
- Tang, O. and S.N. Musa, 2011. Identifying risk issues and research advancements in supply chain risk management. *International Journal of Production Economics* 133(1): 25-34.
- Tapiero, C.S., 2008. Orders and inventory commodities with price and demand uncertainty in complete markets. *International Journal of Production Economics* 115(1): 12-18.

Wagner, S.M., C. Bode and P. Koziol, 2009. Supplier default dependencies: Empirical evidence from the automotive industry. *European Journal of Operational Research* 199(1): 150-161.

Wang, Y. and B. Tomlin, 2009. To wait or not to wait: Optimal ordering under lead time uncertainty and forecast updating. *Naval Research Logistics* 56(8): 766-779.

Ward, A., 2011. Apple overtakes Nokia in smartphone stakes. *Financial Times*. <http://www.ft.com/cms/s/0/4d7fd1e2-b38e-11e0-b56c-00144feabdc0.html#axzz1StIJZLy7>, accessed on 23rd May, 2012.

Watts, C.A., K.Y. Kim and C.K. Hahn, 1995. Linking purchasing to corporate competitive strategy. *International Journal of Supply Chain Management* 31(2): 2-8.

Weele, A., 1994. *Purchasing Management: Analysis, Planning and Practice*. Chapman and Hall, London.

Weng, Z. and T. McClurg, 2003. Coordinated ordering decisions for short life cycle products with uncertainty in delivery time and demand. *European Journal of Operational Research* 151(1): 12-24.

Wilson, E.J., 1994. The relative importance of supplier selection criteria: A review and update. *International Journal of Purchasing and Materials Management* 30(3): 35-41.

Wilson, M., 2007. The impact of transportation disruptions on supply chain performance. *Transportation Research Part E: Logistics and Transportation Review* 43(4): 295-320.

Woo, C.K., I. Horowitz, A. Olson, B. Horii and C. Baskette, 2006. Efficient frontiers for electricity procurement by an LDC with multiple purchase options. *Omega* 34(1): 70-80.

Xiong, H.C., B.T. Chen, and J.X. Xie, 2011. A composite contract based on buy back and quantity flexibility contracts. *European Journal of Operational Research* 210(3): 559-567.

Xu, H., 2010. Managing production and procurement through option contracts in supply chains with random yield. *International Journal of Production Economics* 126(2): 306-313.

Xu, H., N. Shi, S.H. Ma, K.K. Lai, 2010. Contracting with an urgent supplier under cost information asymmetry. *European Journal of Operational Research* 206(2): 374-383.

Yan, H., K. Liu and A. Hsu, 2003. Optimal ordering in a dual-supplier system with demand forecast updates. *Production and Operations Management* 12(1): 30-45.

Yan, X. and K. Liu, 2009. An inventory system with two suppliers and default risk. *Operations Research Letters* 37(5): 322-326.

Yang, S., J. Yang and L. Abdel-Malek, 2007. Sourcing with random yields and stochastic demand: A newsvendor approach. *Computers and Operations Research* 34(12): 3682-3690.

Yano, C. and H. Lee, 1995. Lot sizing with random yields: A review. *Operations Research* 43(2): 311-334.

Yeo W.M. and X.M. Yuan, 2011. Optimal inventory policy with supply uncertainty and demand cancellation. *European Journal of Operational Research* 211(1): 26-34.

Yi, J.X. and A. Scheller-Wolf , 2003. Dual sourcing from a regular supplier and a spot market. GSIA-Carnegie Mellon University, working paper.

Zare, K., A. J. Conejo, M. Carrión and M. P. Moghaddam, 2010. Multi-market energy procurement for a large consumer using a risk-aversion procedure. *Electric Power Systems Research* 80(1): 63-70.

Zhang, F., 2010. Procurement mechanism design in a two-echelon inventory system with price-sensitive demand. *Manufacturing and Service Operations Management* 12(4): 608-626.

Zhang, G.Q. and L.P. Ma, 2009. Optimal acquisition policy with quantity discounts and uncertain demands. *International Journal of Production Research* 47(9): 2409-2425.

Zhang, J. and M. Zhang, 2010. Supplier selection and purchase problem with fixed cost and constrained order quantities under stochastic demand. *International Journal of Production Economics* 129(1): 1-7.

Zhao, Y.X., S.W. Wang, T.C.E. Cheng, X.Q. Yang and Z.M. Huang, 2010. Coordination of supply chains by option contracts: A cooperation game theory approach. *European Journal of Operational Research* 207(2): 668-675.

Zimberg, B. and C. Testuri, 2006. Stochastic analysis of crude oil procurement and processing under uncertain demand for bunker fuel oil. *International Transactions in Operational Research* 13(5): 387-402.

Appendix 1: Derivation of the expected profit for the BS model

Under the assumption of buying and selling, the buyer's profit can be expressed as follows:

$$\Pi_{BS} = rd + s(Y - d) - wY.$$

So, the expected value of the buyer's profit can be computed as follows:

$$\begin{aligned} E(\Pi_{BS}) &= E[rd + s(Y - d) - wY] \\ &= E(rd) + E(sY) - E(sd) - E(wY) \\ &= r\mu_d + (\mu_s\mu_Y + \rho_{y,s}\sigma_s\sigma_Y) - (\mu_s\mu_d + \rho_{d,s}\sigma_s\sigma_d) - w\mu_Y \\ &= (r - \mu_s)\mu_d - \rho_{d,s}\sigma_d\sigma_s + [(\mu_s - w)\mu_Y + \rho_{y,s}\sigma_Y\sigma_s]Q. \end{aligned}$$

Appendix 2: Derivation of the profit variance for the BS model

The variance of the buyer's profit can be computed as follows:

$$\begin{aligned} Var(\Pi_{BS}) &= E[(\Pi_{BS})^2] - [E(\Pi_{BS})]^2 \\ &= E\{[rd + s(Y - d) - wY]^2\} - [E(\Pi_{BS})]^2 \\ &= E[(r - s)^2d^2] + 2E[dY(r - s)(s - w)] + E[(s - w)^2Y^2] - [E(\Pi_{BS})]^2. \end{aligned}$$

As for $E[(r - s)^2d^2]$, we have that

$$\begin{aligned} E[(r - s)^2d^2] &= Var[(r - s)d] + \{E[(r - s)d]\}^2 \\ &= [E(r - s)]^2Var(d) + Var(r - s)[E(d)]^2 + Var(r - s)Var(d) \\ &\quad + 2E(s - r)E(d)Cov(s - r, d) + [Cov(s - r, d)]^2 + \{E[(r - s)d]\}^2 \\ &= (r - \mu_s)^2\sigma_d^2 + \sigma_s^2\mu_d^2 + \sigma_s^2\sigma_d^2 + 2(\mu_s - r)\mu_d\rho_{d,s}\sigma_s\sigma_d + \rho_{d,s}^2\sigma_s^2\sigma_d^2 \\ &\quad + [(r - \mu_s)\mu_d - \rho_{d,s}\sigma_s\sigma_d]^2 \\ &= [(r - \mu_s)^2 + \sigma_s^2](\mu_d^2 + \sigma_d^2) + 2\rho_{d,s}^2\sigma_s^2\sigma_d^2 - 4\rho_{d,s}\sigma_s\sigma_d\mu_d(r - \mu_s). \end{aligned}$$

The calculation process of $E[(s - w)^2 Y^2]$ is similar to that of $E[(r - s)^2 d^2]$, and the result is as follows:

$$E[(s - w)^2 Y^2] = [(w - \mu_s)^2 + \sigma_s^2](\mu_Y^2 + \sigma_Y^2) + 2\rho_{Y,s}^2 \sigma_s^2 \sigma_Y^2 - 4\rho_{Y,s} \sigma_s \sigma_Y \mu_Y (w - \mu_s).$$

As for $E[dY(r - s)(s - w)]$, defining $u = s - r$ and $v = s - w$, we have that $E[dY(r - s)(s - w)] = -E(dYuv)$. Moreover, $E(dYuv) = E(dY \cdot uv) = E(dY)E(uv) + Cov(dY, uv)$, where $E(dY) = \mu_d \mu_Y + \rho_{d,Y} \sigma_d \sigma_Y$ and $E(uv) = E(s^2 - sw - rs + rw) = (\mu_s^2 + \sigma_s^2) - (w + r)\mu_s + rw = (\mu_s - w)(\mu_s - r) + \sigma_s^2$.

Before we compute $Cov(dY, uv)$, let's introduce an important result from Bohrnstedt and Goldberger (1969). Let x_1, x_2, x_3 , and x_4 be jointly distributed random variables. By definition, the covariance between products $x_1 x_2$ and $x_3 x_4$ is as follows:

$$C(x_1 x_2, x_3 x_4) = E\{[x_1 x_2 - E(x_1 x_2)][x_3 x_4 - E(x_3 x_4)]\},$$

where C is short for covariance. Let $\Delta x_1 = x_1 - E(x_1)$, $\Delta x_2 = x_2 - E(x_2)$, $\Delta x_3 = x_3 - E(x_3)$, and $\Delta x_4 = x_4 - E(x_4)$. We have that

$$\begin{aligned} C(x_1 x_2, x_3 x_4) &= E(x_1)E(x_3)C(x_2, x_4) + E(x_1)E(x_4)C(x_2, x_3) + E(x_2)E(x_3)C(x_1, x_4) \\ &\quad + E(x_2)E(x_4)C(x_1, x_3) + E(\Delta x_1 \Delta x_2 \Delta x_3 \Delta x_4) \\ &\quad + E(x_1)E(\Delta x_2 \Delta x_3 \Delta x_4) + E(x_2)E(\Delta x_1 \Delta x_3 \Delta x_4) \\ &\quad + E(x_3)E(\Delta x_1 \Delta x_2 \Delta x_4) + E(x_4)E(\Delta x_1 \Delta x_2 \Delta x_3) \\ &\quad - C(x_1, x_2)C(x_3, x_4). \end{aligned}$$

Based on the result from Anderson (1958), under multivariate normality, all third moments vanish and

$$E(\Delta x_1 \Delta x_2 \Delta x_3 \Delta x_4) = C(x_1, x_2)C(x_3, x_4) + C(x_1, x_3)C(x_2, x_4) + C(x_1, x_4)C(x_2, x_3).$$

Therefore,

$$C(x_1 x_2, x_3 x_4) = E(x_1)E(x_3)C(x_2, x_4) + E(x_1)E(x_4)C(x_2, x_3) + E(x_2)E(x_3)C(x_1, x_4)$$

$$+E(x_2)E(x_4)C(x_1, x_3) + C(x_1, x_3)C(x_2, x_4) + C(x_1, x_4)C(x_2, x_3).$$

Hence,

$$\begin{aligned} C(dY, uv) &= E(d)E(u)C(Y, v) + E(d)E(v)C(Y, u) + E(Y)E(u)C(d, v) \\ &\quad + E(Y)E(v)C(d, u) + C(d, u)C(Y, v) + C(d, v)C(Y, u). \end{aligned}$$

Because $C(Y, u) = C(Y, s - r) = E\{[Y - E(Y)][(s - r) - E(s - r)]\} = E\{[Y - E(Y)][s - E(s)]\} = C(Y, s)$ and $C(Y, v) = C(Y, s)$, we have that $C(Y, u) = C(Y, v) = C(Y, s)$.

Thus,

$$\begin{aligned} C(dY, uv) &= E(d)E(u)C(Y, s) + E(d)E(v)C(Y, s) + E(Y)E(u)C(d, s) \\ &\quad + E(Y)E(v)C(d, s) + 2C(d, s)C(Y, s) \\ &= \mu_d(\mu_s - r)\rho_{y,s}\sigma_Y\sigma_s + \mu_d(\mu_s - w)\rho_{y,s}\sigma_Y\sigma_s + \mu_Y(\mu_s - r)\rho_{d,s}\sigma_d\sigma_s \\ &\quad + \mu_Y(\mu_s - w)\rho_{d,s}\sigma_d\sigma_s + 2\rho_{d,s}\sigma_d\sigma_s\rho_{y,s}\sigma_Y\sigma_s \\ &= (2\mu_s - r - w)\sigma_s(\mu_d\rho_{y,s}\sigma_Y + \mu_Y\rho_{d,s}\sigma_d) + 2\rho_{d,s}\sigma_d\sigma_s\rho_{y,s}\sigma_Y\sigma_s. \end{aligned}$$

Therefore, the profit variance is computed as follows:

$$\begin{aligned} \text{Var}(\Pi_{BS}) &= E[(r - s)^2 d^2] + 2E[dY(r - s)(s - w)] + E[(s - w)^2 Y^2] - [E(\Pi_{BS})]^2 \\ &= E[(r - s)^2 d^2] + E[(s - w)^2 Y^2] - 2[E(dY)E(uv) + C(dY, uv)] \\ &\quad - [E(\Pi_{BS})]^2 \\ &= [(r - \mu_s)^2 + \sigma_s^2](\mu_d^2 + \sigma_d^2) + 2\rho_{d,s}^2\sigma_s^2\sigma_d^2 - 4\rho_{d,s}\sigma_s\sigma_d\mu_d(r - \mu_s) \\ &\quad + [(w - \mu_s)^2 + \sigma_s^2](\mu_Y^2 + \sigma_Y^2) + 2\rho_{y,s}^2\sigma_s^2\sigma_Y^2 - 4\rho_{y,s}\sigma_s\sigma_Y\mu_Y(w - \mu_s) \\ &\quad - 2(\mu_d\mu_Y + \rho_{d,y}\sigma_d\sigma_Y)[(\mu_s - w)(\mu_s - r) + \sigma_s^2] \\ &\quad - 2(2\mu_s - r - w)\sigma_s(\mu_d\rho_{y,s}\sigma_Y + \mu_Y\rho_{d,s}\sigma_d) - 4\rho_{d,s}\sigma_d\sigma_s\rho_{y,s}\sigma_Y\sigma_s - [E(\Pi_{BS})]^2. \end{aligned}$$

The square of the buyer's expected profit is as follows:

$$[E(\Pi_{BS})]^2 = [(r - \mu_s)\mu_d + (\mu_s - w)\mu_Y + (\rho_{y,s}\sigma_Y - \rho_{d,s}\sigma_d)\sigma_s]^2$$

$$\begin{aligned}
&= (r - \mu_s)^2 \mu_d^2 + (\mu_s - w)^2 \mu_Y^2 + \rho_{y,s}^2 \sigma_s^2 \sigma_Y^2 + \rho_{d,s}^2 \sigma_s^2 \sigma_d^2 - 2\rho_{d,s} \sigma_d \sigma_s \rho_{y,s} \sigma_Y \sigma_s \\
&\quad + 2\mu_d \mu_Y (r - \mu_s)(\mu_s - w) + 2(r - \mu_s) \mu_d (\rho_{y,s} \sigma_Y - \rho_{d,s} \sigma_d) \sigma_s \\
&\quad + 2(\mu_s - w) \mu_Y (\rho_{y,s} \sigma_Y - \rho_{d,s} \sigma_d) \sigma_s.
\end{aligned}$$

After substituting $[E(\Pi_{BS})]^2$ into $Var(\Pi_{BS})$, we have that

$$\begin{aligned}
Var(\Pi_{BS}) &= (r - \mu_s)^2 \sigma_d^2 + (\mu_s - w)^2 \sigma_Y^2 + \sigma_s^2 (\mu_Y^2 + \sigma_Y^2 + \mu_d^2 + \sigma_d^2 + \rho_{d,s}^2 \sigma_d^2 + \rho_{y,s}^2 \sigma_Y^2 \\
&\quad - 2\mu_Y \mu_d) - 2\rho_{d,s} \sigma_d \sigma_s (r - \mu_s)(\mu_d - \mu_Y) - 2\rho_{y,s} \sigma_s \sigma_Y (\mu_s - w)(\mu_d - \mu_Y) \\
&\quad - 2\rho_{d,s} \rho_{y,s} \sigma_d \sigma_Y \sigma_s^2 - 2\rho_{d,y} \sigma_d \sigma_Y [(\mu_s - r)(\mu_s - w) + \sigma_s^2].
\end{aligned}$$

Appendix 3: Proof of Proposition 1

Since $\mu_Y = \mu_y Q$ and $\sigma_Y = \sigma_y Q$, substituting them into $Var(\Pi_{BS})$, we obtain that

$$\begin{aligned}
Var(\Pi_{BS}) &= (r - \mu_s)^2 \sigma_d^2 + (\mu_s - w)^2 \sigma_y^2 Q^2 + \sigma_s^2 (\mu_y^2 Q^2 + \sigma_y^2 Q^2 + \mu_d^2 + \sigma_d^2 + \rho_{d,s}^2 \sigma_d^2 \\
&\quad + \rho_{y,s}^2 \sigma_y^2 Q^2 - 2\mu_y Q \mu_d) - 2\rho_{d,s} \sigma_d \sigma_s (r - \mu_s)(\mu_d - \mu_y Q) \\
&\quad - 2\rho_{y,s} \sigma_s \sigma_y Q (\mu_s - w)(\mu_d - \mu_y Q) - 2\rho_{d,s} \rho_{y,s} \sigma_d \sigma_y Q \sigma_s^2 \\
&\quad - 2\rho_{d,y} \sigma_d \sigma_y Q [(\mu_s - r)(\mu_s - w) + \sigma_s^2] \\
&= [(\mu_s - w)^2 \sigma_y^2 + (\mu_y^2 + \sigma_y^2) \sigma_s^2 + \rho_{y,s}^2 \sigma_y^2 \sigma_s^2 + 2\rho_{y,s} \sigma_s \sigma_y \mu_y (\mu_s - w)] Q^2 \\
&\quad - 2\{\mu_y \mu_d \sigma_s^2 - \rho_{d,s} \sigma_d \sigma_s \mu_y (r - \mu_s) + \rho_{y,s} \sigma_s \sigma_y \mu_d (\mu_s - w) \\
&\quad + \rho_{d,s} \rho_{y,s} \sigma_d \sigma_y \sigma_s^2 + \rho_{d,y} \sigma_d \sigma_y [(\mu_s - r)(\mu_s - w) + \sigma_s^2]\} Q + (r - \mu_s)^2 \sigma_d^2 \\
&\quad + (\mu_d^2 + \sigma_d^2 + \rho_{d,s}^2 \sigma_d^2) \sigma_s^2 - 2\rho_{d,s} \sigma_d \sigma_s \mu_d (r - \mu_s).
\end{aligned}$$

Then, we find that $Var(\Pi_{BS})$ is a quadratic function with the form of $f(Q) = aQ^2 + bQ + c$, where

$$a = (\mu_s - w)^2 \sigma_y^2 + (\mu_y^2 + \sigma_y^2) \sigma_s^2 + \rho_{y,s}^2 \sigma_y^2 \sigma_s^2 + 2\rho_{y,s} \sigma_s \sigma_y \mu_y (\mu_s - w)$$

$$\begin{aligned}
&= [(\mu_s - w)\sigma_y + \rho_{y,s}\mu_y\sigma_s]^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 - \rho_{y,s}^2\sigma_s^2\mu_y^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 \\
&= [(\mu_s - w)\sigma_y + \rho_{y,s}\mu_y\sigma_s]^2 + (1 - \rho_{y,s}^2)\sigma_s^2\mu_y^2 + (1 + \rho_{y,s}^2)\sigma_s^2\sigma_y^2.
\end{aligned}$$

Since $0 \leq \rho_{y,s}^2 \leq 1$, we have that $a > 0$. Therefore, the parabola opens upward.

Appendix 4: Derivation of the optimal order quantity Q^*

The objective function $Z(Q)$ equals to $E(\Pi_{BS}) - kVar(\Pi_{BS})$. Since $Y = yQ$, $\mu_Y = \mu_y Q$, and $\sigma_Y = \sigma_y Q$, substituting them into $Z(Q)$, we obtain that

$$\begin{aligned}
Z(Q) &= \mu_d(r - \mu_s) + \mu_y Q(\mu_s - w) + \sigma_s(\rho_{y,s}\sigma_y Q - \rho_{d,s}\sigma_d) \\
&\quad - k\{(r - \mu_s)^2\sigma_d^2 + (\mu_s - w)^2\sigma_y^2 Q^2 \\
&\quad + \sigma_s^2(\mu_y^2 Q^2 + \sigma_y^2 Q^2 + \mu_d^2 + \sigma_d^2 + \rho_{d,s}^2\sigma_d^2 + \rho_{y,s}^2\sigma_y^2 Q^2 - 2\mu_y Q\mu_d) \\
&\quad - 2\rho_{d,s}\sigma_d\sigma_s(r - \mu_s)(\mu_d - \mu_y Q) - 2\rho_{y,s}\sigma_s\sigma_y Q(\mu_s - w)(\mu_d - \mu_y Q) \\
&\quad - 2\rho_{d,s}\rho_{y,s}\sigma_d\sigma_y Q\sigma_s^2 - 2\rho_{d,y}\sigma_d\sigma_y Q[(\mu_s - r)(\mu_s - w) + \sigma_s^2]\}.
\end{aligned}$$

Thus,

$$\begin{aligned}
\frac{d^2 Z(Q)}{dQ^2} &= -k[2(w - \mu_s)^2\sigma_y^2 + 2\sigma_s^2(\mu_y^2 + \sigma_y^2) + 2\rho_{y,s}^2\sigma_s^2\sigma_y^2 + 4(\mu_s - w)\rho_{y,s}\mu_y\sigma_s\sigma_y] \\
&= -2k\left\{[(\mu_s - w)\sigma_y + \rho_{y,s}\mu_y\sigma_s]^2 + \sigma_s^2[(1 - \rho_{y,s}^2)\mu_y^2 + (1 + \rho_{y,s}^2)\sigma_y^2]\right\}.
\end{aligned}$$

Since $\rho_{y,s}$ is a correlation coefficient, we have that $1 - \rho_{y,s}^2 \geq 0$. Therefore, $\frac{d^2 Z(Q)}{dQ^2} \leq 0$.

So, $Z(Q)$ is concave and the optimal order quantity Q^* can be obtained through $\frac{dZ(Q)}{dQ} = 0$.

Based on the expression of $Z(Q)$, we have that

$$\begin{aligned}
\frac{dZ(Q)}{dQ} = & \mu_y(\mu_s - w) + \rho_{y,s}\sigma_y\sigma_s \\
& + 2k\{\mu_y\mu_d\sigma_s^2 - \rho_{d,s}\mu_y\sigma_s\sigma_d(r - \mu_s) + \rho_{y,s}\mu_d\sigma_s\sigma_y(\mu_s - w) \\
& + \rho_{d,s}\rho_{y,s}\sigma_d\sigma_y\sigma_s^2 + \rho_{d,y}\sigma_d\sigma_y[(\mu_s - r)(\mu_s - w) + \sigma_s^2]\} \\
& - 2kQ[(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w)].
\end{aligned}$$

Let $\frac{dZ(Q)}{dQ} = 0$. Then, the optimal order quantity is as follows:

$$\begin{aligned}
& \frac{(\mu_s - w)\mu_y + \rho_{y,s}\sigma_y\sigma_s}{2k} + \frac{\mu_d\mu_y\sigma_s^2 - \rho_{d,s}\mu_y\sigma_s\sigma_d(r - \mu_s) + \rho_{y,s}\mu_d\sigma_s\sigma_y(\mu_s - w)}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w)} \\
& + \frac{\rho_{d,s}\rho_{y,s}\sigma_d\sigma_y\sigma_s^2 + \rho_{d,y}\sigma_d\sigma_y[(\mu_s - r)(\mu_s - w) + \sigma_s^2]}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w)}.
\end{aligned}$$

Appendix 5: Proof of Proposition 2

Based on the analytical expression of the optimal order quantity Q^* , $\frac{dQ^*}{d\rho_{d,y}}$ is computed

as follows:

$$\frac{dQ^*}{d\rho_{d,y}} = \frac{\sigma_d\sigma_y[(\mu_s - r)(\mu_s - w) + \sigma_s^2]}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w)}.$$

Since $\rho_{d,y} < 0$, in order to investigate the effect of $\rho_{d,y}$ on the optimal order quantity Q^* ,

we need to calculate $\frac{dQ^*}{d(-\rho_{d,y})}$, which is computed as follows:

$$\frac{dQ^*}{d(-\rho_{d,y})} = \frac{-\sigma_d\sigma_y[(\mu_s - r)(\mu_s - w) + \sigma_s^2]}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w)}.$$

Let $\frac{dQ^*}{d(-\rho_{d,y})} > 0$, we have that $\frac{-\sigma_d\sigma_y[(\mu_s - r)(\mu_s - w) + \sigma_s^2]}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w)} > 0$.

According to a conclusion in Appendix 3, $(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 +$

$2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w) > 0$. So, to guarantee that $\frac{dQ^*}{d(-\rho_{d,y})} > 0$, we should have that $-\sigma_d\sigma_y[(\mu_s - r)(\mu_s - w) + \sigma_s^2] > 0$.

Appendix 6: Proof of Proposition 3

Based on the analytical expression of the optimal order quantity Q^* , $\frac{dQ^*}{d\rho_{d,s}}$ is computed as follows:

$$\frac{dQ^*}{d\rho_{d,s}} = \frac{-\sigma_d\sigma_s[\mu_y(r - \mu_s) - \rho_{y,s}\sigma_s\sigma_y]}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w)}.$$

Since $(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2 + \rho_{y,s}^2\sigma_y^2\sigma_s^2 + 2\rho_{y,s}\mu_y\sigma_s\sigma_y(\mu_s - w) > 0$, to guarantee that $\frac{dQ^*}{d\rho_{d,s}} > 0$, $-\sigma_d\sigma_s[\mu_y(r - \mu_s) - \rho_{y,s}\sigma_s\sigma_y]$ must be greater than 0.

Appendix 7: Proof of Proposition 4

When all the risks are not correlated, we have that

$$Q^* = \frac{\frac{(\mu_s - w)\mu_y}{2k} + \mu_d\mu_y\sigma_s^2}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2}.$$

$$\text{Thus, } \frac{dQ^*}{d\mu_d} = \frac{\mu_y\sigma_s^2}{(w - \mu_s)^2\sigma_y^2 + (\mu_y^2 + \sigma_y^2)\sigma_s^2} > 0.$$

Appendix 8: Proof of Proposition 5

When all the risks are not correlated, we have that

$$\begin{aligned}\frac{dQ^*}{d\mu_y} &= \frac{\left(\frac{\mu_s - w}{2k} + \mu_d \sigma_s^2\right) [(w - \mu_s)^2 \sigma_y^2 + (\mu_y^2 + \sigma_y^2) \sigma_s^2] - 2\mu_y \sigma_s^2 \left[\frac{(\mu_s - w)\mu_y}{2k} + \mu_d \mu_y \sigma_s^2\right]}{[(w - \mu_s)^2 \sigma_y^2 + (\mu_y^2 + \sigma_y^2) \sigma_s^2]^2} \\ &= \frac{\left(\frac{\mu_s - w}{2k} + \mu_d \sigma_s^2\right) [(w - \mu_s)^2 \sigma_y^2 + (\sigma_y^2 - \mu_y^2) \sigma_s^2]}{[(w - \mu_s)^2 \sigma_y^2 + (\mu_y^2 + \sigma_y^2) \sigma_s^2]^2}.\end{aligned}$$

To guarantee that $\frac{dQ^*}{d\mu_y} > 0$, we must have that $\left(\frac{\mu_s - w}{2k} + \mu_d \sigma_s^2\right) [(w - \mu_s)^2 \sigma_y^2 + (\sigma_y^2 - \mu_y^2) \sigma_s^2] > 0$.